4-20-2021

CO2 Sequestration by Allam Cycle

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Abstract

Natural gas powerplants account for 40% of the electricity generation in the United States[1] and 617 million tons of CO_2 emissions a year[2]. The largest powerplants with carbon capture technology utilize a post-combustion absorption technology that must treat a large volume of flue gas and compress CO_2 to pipeline specifications from near-ambient pressure. The Allam cycle, patented in 2013 by Rodney Allam, uses oxy-combustion and a supercritical CO_2 stream as the working fluid to produce high-purity liquid pipeline CO_2. While it was developed commercially at a 50-megawatt thermal (MWt) plant in 2018, the economics for a larger, 300 MW plant had not been documented. This project shows that under the current US tax code, the Allam cycle is less economical than the traditional natural gas combined cycle (NGCC) and NGCC with CDR. However, due to the over 99% capture rate, compared to 90% in post-combustion capture, the breakeven credit to traditional NGCC of $112/tonne for the Allam cycle is lower than the NGCC with CDR breakeven credit of $121/tonne. Similarly, for a desired IRR of 15%, the CO2 credit required for the Allam cycle is $163/tonne compared to $188/tonne for the NGCC with CDR. The Allam cycle provides increasingly better financial returns than the NGCC with CDR as the tax credit for sequestration rises. The results of this analysis were produced by first simulating both powerplants in Aspen Plus, and then conducting a discounted cash flow analysis for various scenarios.

Disciplines

Biochemical and Biomolecular Engineering | Chemical Engineering | Engineering

Letter of Transmittal

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220 S. 33rd Street
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April 20th, 2021

Dear Mr. Bruce Vrana, Dr. Warren Seider, and Mr. Adam Brostow,

The enclosed report contains a comparison of the Allam cycle with the natural gas-fired combined cycle (NGCC), as proposed by Mr. Adam Brostow. The cost and performance of the NGCC with a post-combustion carbon dioxide removal (CDR) facility is also considered. Two, 300 MW powerplants were designed in Aspen Plus, and OPEX and CAPEX were calculated from the results.

Due to the large capital investment, the Allam cycle has a negative NPV of -$648MM, lower than both the NGCC and NGCC with CDR. However, because the Allam cycle is able to capture over 99%, compared to 90% in a post-combustion process, the breakeven CO_2 credit of $112/tonne to be equivalent to the traditional NGCC and $163/tonne to yield a 15% IRR is lower than that of the NGCC with CDR. There is also a potential revenue stream from the high purity nitrogen byproduct from the integrated air separation unit (ASU).

While we do not recommend the Allam cycle from an economic standpoint, the larger CO_2 capture rate could make it more economical under future tax policy.

We greatly appreciate the support you provided throughout the entire semester.

Sincerely,

Raghav Chaturvedi | Eric Kennedy | Sarron Metew

CO_2 Sequestration by Allam Cycle

Raghav Chaturvedi
Eric Kennedy
Sarron Metew

Project Author: Mr. Adam Brostow
Project Advisor: Dr. Warren Seider

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School of Engineering and Applied Sciences
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April 20, 2021

Contents

Abstract

4.1. Abstract

Natural gas powerplants account for 40% of the electricity generation in the United States[1] and 617 million tons of CO_2 emissions a year[2]. The largest powerplants with carbon capture technology utilize a post-combustion absorption technology that must treat a large volume of flue gas and compress CO_2 to pipeline specifications from near-ambient pressure. The Allam cycle, patented in 2013 by Rodney Allam, uses oxy-combustion and a supercritical CO_2 stream as the working fluid to produce high-purity liquid pipeline CO_2. While it was developed commercially at a 50-megawatt thermal (MWt) plant in 2018, the economics for a larger, 300 MW plant had not been documented. This project shows that under the current US tax code, the Allam cycle is less economical than the traditional natural gas combined cycle (NGCC) and NGCC with CDR. However, due to the over 99% capture rate, compared to 90% in post-combustion capture, the breakeven credit to traditional NGCC of $112/tonne for the Allam cycle is lower than the NGCC with CDR breakeven credit of $121/tonne. Similarly, for a desired IRR of 15%, the CO2 credit required for the Allam cycle is $163/tonne compared to $188/tonne for the NGCC with CDR. The Allam cycle provides increasingly better financial returns than the NGCC with CDR as the tax credit for sequestration rises. The results of this analysis were produced by first simulating both powerplants in Aspen Plus, and then conducting a discounted cash flow analysis for various scenarios.

List of Figures and Tables

Introduction and Objective – Time Chart

5.1. Project Motivation

Electricity generation from natural gas combustion accounted for 617 million tons of CO_2 emissions in the US in 2019 [2]. While wind and solar are becoming increasingly popular, natural gas still accounts for 40% of the total market in the US. The 19.3 GW of added natural gas electricity capacity in 2018 was more than 67% than that of wind and solar combined [3].

Of the 19.3 GW of added capacity, almost 90% utilized natural gas-fired combined cycle (NGCC) technology which relies on a combined Brayton and Rankine cycle to increase the efficiency of a simple-cycle turbine. Due to the massive scale of the natural gas market and threat of climate change, there is increasing effort to develop technologies to capture and sequester CO_2 from natural gas powerplants.

Post-combustion capture using amine-based absorption can be retrofitted to existing plants, separating CO_2 from the flue gas. The Petra Nova project in Texas captured over a million tons of CO_2 a year from a post-coal-combustion flue gas, before shutting down due to falling oil prices as a result of the Covid-19 pandemic.

The Allam cycle, patented in 2013, utilizes oxy-fuel combustion and a supercritical CO_2 stream as the working fluid to successfully sequester CO_2. NET Power demonstrated the Allam cycle at a 50 MWt plant in 2018, but the economics of a larger, 300 MW plant are not documented. It is desired to compare the economics of post-combustion capture and the Allam cycle to the more profitable but less environmentally friendly traditional NGCC.

5.2. Project Goals

The goal of this project was to model and cost three powerplants: traditional NGCC, NGCC with post-combustion capture, and the Allam cycle. The economic and environmental impacts of the three powerplants were compared under similar thermodynamic performance and costing assumptions. Although rigorous modeling of post-combustion capture in the NGCC is beyond the scope of this project, capital and operating costs of amine scrubbing units are well documented in the literature. Capturing CO_2, whether by post-combustion or Allam cycle, was accepted to be less economical from the start, but it is ultimately desired to determine a breakeven CO_2 credit, which could be funded via tax-credit, demand as feedstock to enhanced oil recovery (EOR), or a combination of the two.

5.3. Time Chart

Figure 5.1 details the time chart for successful completion of this project. Intermediate deadlines included a mass balance, process flow diagram (PFD), mid-semester presentation, equipment design, and profitability analysis.

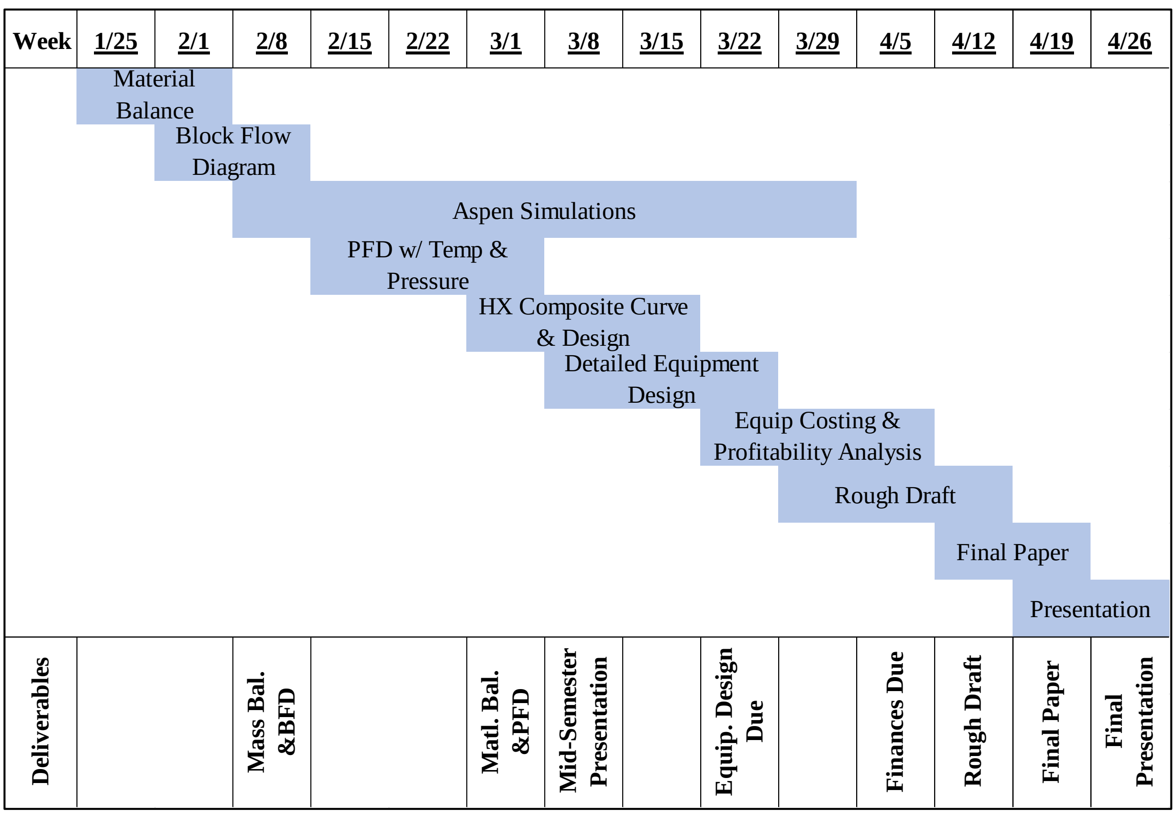

Figure 5.1: Time Chart for the project, 'Clean Energy with CO_2 Sequestration by Allam Cycle

5.4. Project Deliverables

The NGCC and Allam cycle with integrated air separation unit (ASU) were modelled in Aspen Plus, and the simulation results are included in the report. Total capital investments were estimated by the design and costing of the major equipment; although, rigorous design of all unit operations, particularly the amine scrubbing unit, is beyond the scope of this project. The results provide capital expenditure (CAPEX), operating expenditure (OPEX), and profitability analysis for three powerplants. Because profitability is largely dependent on emission guidelines and incentives for CO_2 capture, recommendations were made based on various government policies and tax incentives.

All costs and sales are assumed to occur within the battery limits of the plants, plus a 10-mile investment of necessary pipeline infrastructure. Variables outside of natural gas feedstock, pipeline CO_2, and electricity generation are independent of the operations within the plant. Concerns outside of the set boundaries, such as fracking and CO_2 leakage in the sourcing of natural gas or electricity transmission and distribution, should be considered but are not analyzed in this project. Furthermore, implications on funding for other environmental projects, such as wind and solar, are not analyzed. This is strictly a comparative analysis of the NGCC, NGCC with post-combustion capture, and Allam cycle.

6. The Innovation Map section has been removed from the process design report.

Market and Competitive Analysis

7.1. Market and Competitive Analysis

Electricity demand, natural gas supply, and CO_2 pipeline demand are the three fundamental markets for consideration.

7.2. US Energy Production Overview

The power grids in the U.S. contain over 7,300 powerplants and thousands of miles of high and low voltage power lines that connect 145 million customers [5]. There are three main interconnectors that make up the power system and operate independently of one another: the Eastern Interconnection (Great Plains states, excluding Texas, eastward to the Atlantic coast), the Western Interconnection (west of Rocky Mountains and Great Plains to the Pacific Coast), and the Electric Reliability Council of Texas (most of Texas) [5]. This type of network allows the grid to be more economical by allowing generators to be placed in optimal locations and more reliable by providing different paths for the power to flow.

The U.S. electricity market has two components that can be regulated or competitive: wholesale and retail. Wholesale markets involve the sale of electricity among electric utilities and traders before it is sold to consumers. If they are regulated, electric utilities are responsible for the generation, transmission, and distribution of electricity to consumers. If they are competitive, the markets are run by independent system operators so electric utilities distribute electricity to consumers but are less likely to own the generation and transmission. Retail markets, however, involve the sale of electricity to consumers. If they are regulated, consumers do not have the ability to choose who generates their power and must purchase from the utility located in their area but, if they are competitive, consumers can choose between retail suppliers [5].

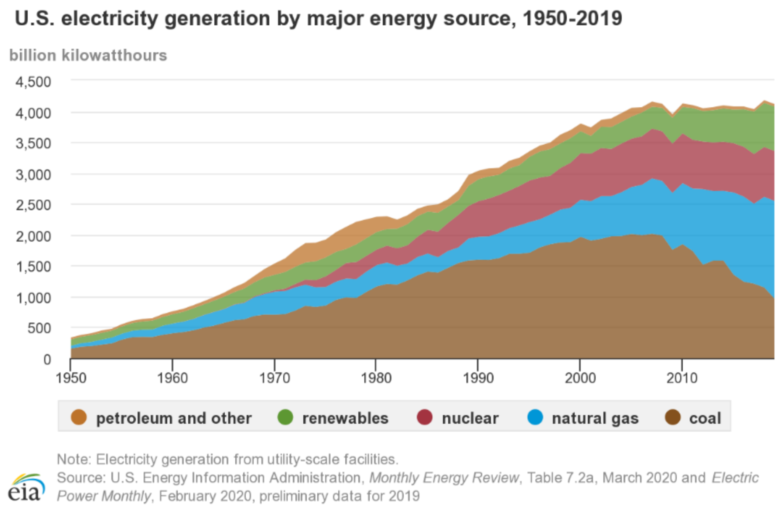

Figure 7.1: Sources of Electricity, from [5]

The distribution of energy sources that generate electricity in the U.S. power grids can be seen in Figure 7.1. Prior to around 2010, the use of coal increased far more quickly than any other energy source. After 2010, coal began to decline while other energy sources like natural gas and renewables continued to increase. This change is mostly due to the growing climate change concerns. Currently coal and natural gas are the two leading energy sources in the U.S.

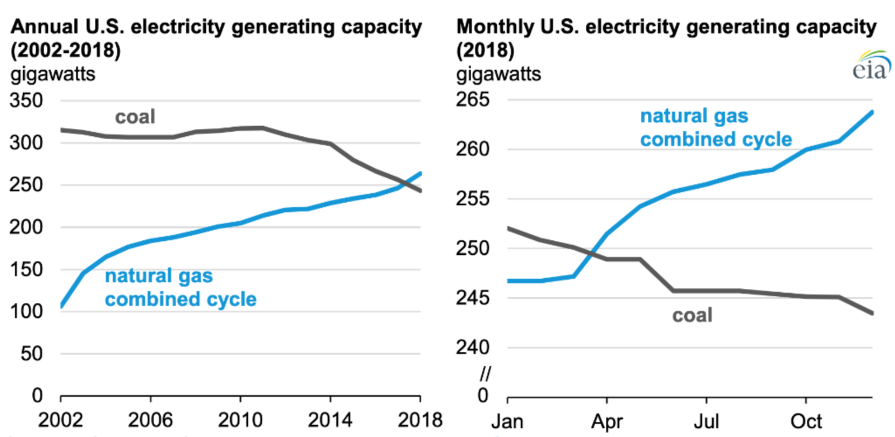

Figure 7.2: Electricity Generating Capacity for Coal Plants vs NGCC, from [6]

Figure 7.2 focuses more specifically on coal and natural gas plants. In 2018, the generating capacity and the electricity generation of natural gas-fired combined cycle (NGCC) plants surpassed that of coal-fired plants. Also, starting in 2015, no new coal-fired plants came online and 40 GW of capacity retired while 30 GW of NGCC net capacity came online [6]. This trend is expected to continue as more NGCC plants come online and coal plants retire.

7.3. US Natural Gas Supply

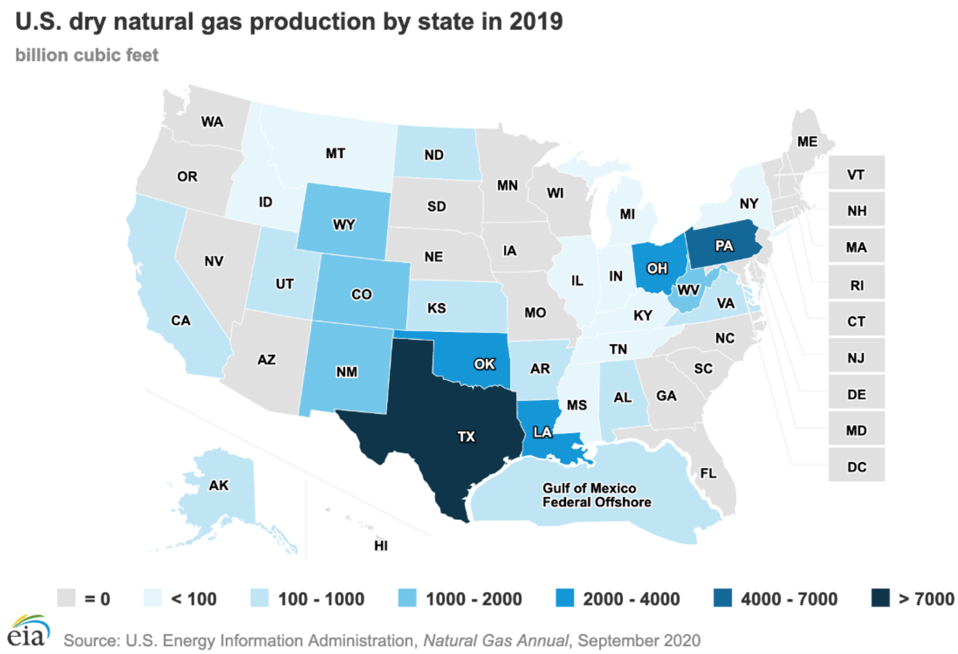

Figure 7.3: Natural Gas Production by State, from [7]

The U.S. produced about 34.4 trillion cubic feet of natural gas in 2020 which was the second highest annual amount [7]. This increase is largely due to horizontal drilling and hydraulic drilling techniques. Most of that natural gas production is heavily concentrated in five states as seen in Figure 7.3. These five states and their share of the total U.S. gas production in 2019 are Texas (23.9%), Pennsylvania (20.0%), Louisiana (9.3%), Oklahoma (8.5%), and Ohio (7.7%) [7].

There are several different sources of natural gas production: coalbed methane and supplemental gaseous fuels, offshore, onshore, and tight/shale gas. Methane obtained from coal seams made up 3% of the total U.S. dry natural gas production in 2019 and additional sources of hydrocarbon gases made up 0.2% of the total U.S. natural gas production in 2020 [7].

Offshore production from ocean water accounted for 0.3% of the total U.S. natural gas production and federal waters in the Gulf of Mexico produced 3% of the total U.S. natural gas production [7]. Shale and tight natural gas have both become increasingly popular in recent years due to commercial and economic success. In fact, they are projected to be the two major contributors to the total U.S. natural gas production through 2050 [7].

7.4. CO_2 Pipeline

Both powerplants will operate in the US Gulf Coast where natural gas supply, electricity demand, and CO_2 pipeline infrastructure are readily available.

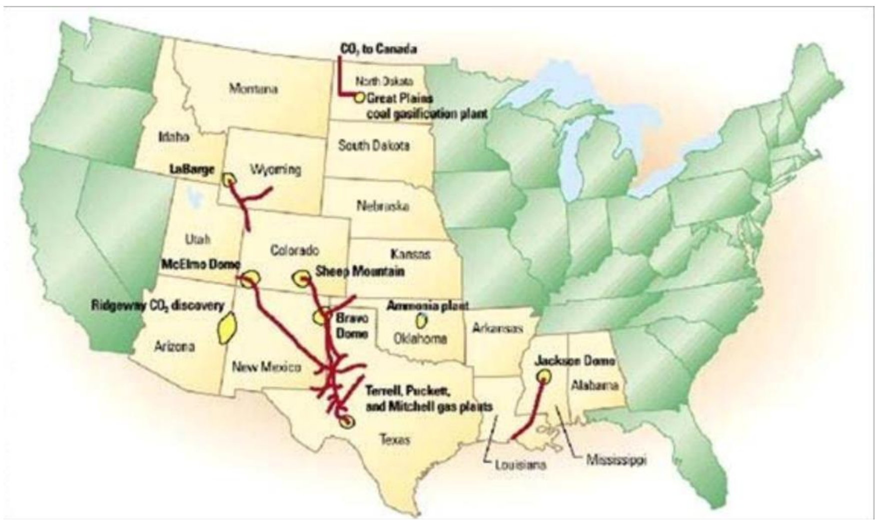

Figure 7.4: Map of CO_2 Pipeline Infrastructure, from [4]

There are currently 3,900 miles of CO_2 pipelines that serve EOR projects in the U.S. [4]. As seen in Figure 7.4, 80% of the existing pipelines were built for the purpose of EOR in the Permian Basin of West Texas [4]. The first pipelines were built in Texas in the 1970s and about three-quarters of the 3,900 miles of CO_2 pipelines were built during the 1980s and 1990s due to energy security concerns and federal tax investments to increase U.S. oil production [4].

Currently, the largest existing pipeline is the 30-inch Cortez Pipeline that was completed in 1983 and runs for more than 500 miles from Colorado to Texas [4]. The size of future pipelines will be determined by climate policies and the location of facilities that utilize carbon capture and storage (CCS) technologies. Based on this, it is estimated that about 11,000-23,000 miles of CO_2 pipeline could be added to the existing network in the U.S. before 2050 [8].

Customer Requirements

8.1. Primary Customer: Electricity Generation

The EIA attributes the pricing of electricity to generation, transmission, and distribution. The purpose of this project is to compare the economic and environmental impact of only the generation segment of overall electricity supply. This approach is sufficient as the differences between the NGCC and Allam cycle are constrained within the boundaries of the powerplant. Section 14.3 shows data from the EIA on each component of electricity sales.

The electricity market in the U.S. is comprised of centralized powerplants and decentralized units where electricity is generated and a system of substations, transformers, and transmission lines that transports electricity to the end user - customer. Due to little storage facilities, energy must be consumed as its produced. There are two types of electricity markets – wholesale and retail, as explained earlier in Section 7. Some parts of the U.S. wholesale electricity market are traditionally regulated, which means that vertically integrated utilities are responsible for the entire flow of electricity to consumers. In a traditionally regulated retail electricity market, consumers cannot choose who generates their power and are required to purchase from the utility in that area.

8.2. CO_2 Pipeline and Tax Credit 45Q

Table 8.1: Quality specifications for pipeline transport of CO_2, from [8]

Component	Concentration limit	Application
H_2O	300–500 ppm	Free water minimization
H_2S	200 ppm	Health and safety
CO	2000 ppm	Health and safety
SO_x	100 ppm	Health and safety
NO_x	100 ppm	Health and safety
O_2	< 4 vol%	Aquifer storage
	< 1000 ppm	EOR technical limit
CH_4	< 4 vol%	Aquifer storage
	< 2 vol%	EOR technical limit
N_2 + Ar + H_2	< 4 vol% total	

Table 8.1 lists the concentration limits for the presence of different components in flue gas for pipeline transport of CO_2. This table was used for the NGCC with CDR and Allam cycle to determine how much N_2 and water could exist in the mostly pure CO_2 stream to be compressed and transported in the pipeline.

The U.S. Department of Energy made a number of tax credits available for clean coal projects in the Energy Policy Act of 2005 (EPAct05). One of the tax credits is Section 45Q. This section provides a tax credit on a per metric ton basis for CO_2 that is sequestered. Section 45Q has been applied and used in the calculations of cash flows for the NGCC with CDR and the Allam Cycle. The tax credit was recently updated in with the passage of the Bipartisan Budget Act of 2018. Credit is available for 12 years and it begins once the plant is in service [9]. For taxpayers who dispose of qualified CO_2 in secure geological storage spaces, an incentive of \$22.66 per metric ton was available in 2017 and increases linearly to \$50 per metric ton in 2026.

9. The CTQ Variables section has been removed from this process design report.

10. The Product Concepts section has been removed from this process design report.

11. The Superior Product Concepts section has been removed from this process design report.

Competitive Patent Analysis

12.1. Allam Cycle Patent Analysis

Construction of the 50 MWt Allam Cycle began in the first quarter of 2016, as reported by Allam et al. in, "Demonstration of the Allam Cycle: An update on the development status of a high efficiency supercritical carbon dioxide power process employing full carbon capture" [10]. The paper cited the original patent, USA Patent 8,596,075 B2 [11].

USA Patent 8,596,075 B2 was published in December of 2013, with Rodney Allam as lead inventor. Figure 12.1 shows, "a flow diagram illustrating a power cycle according to one embodiment of the present disclosure;" as described in the original patent filing. A carbon-based fuel (254), oxygen feed (242), and recycled carbon dioxide stream (236) are fed to the combustor (220). The combustion outlet (40) enters the turbine (320), and the exhaust (50) is cooled in the recuperative heat exchanger (420).

The cooled exhaust (60) enters the separation unit (520), where water (62a) and CO_2 (62b) are separated. A more detailed flow diagram of the separation unit is shown in Figure 12.2. CO_2 (65) exits the separation unit and is compressed (620). Pipeline CO_2 (80) and recycled CO_2 (85) are split by (720), and the recycled CO2 stream is heated in the recuperative heat exchanger (420) [11].

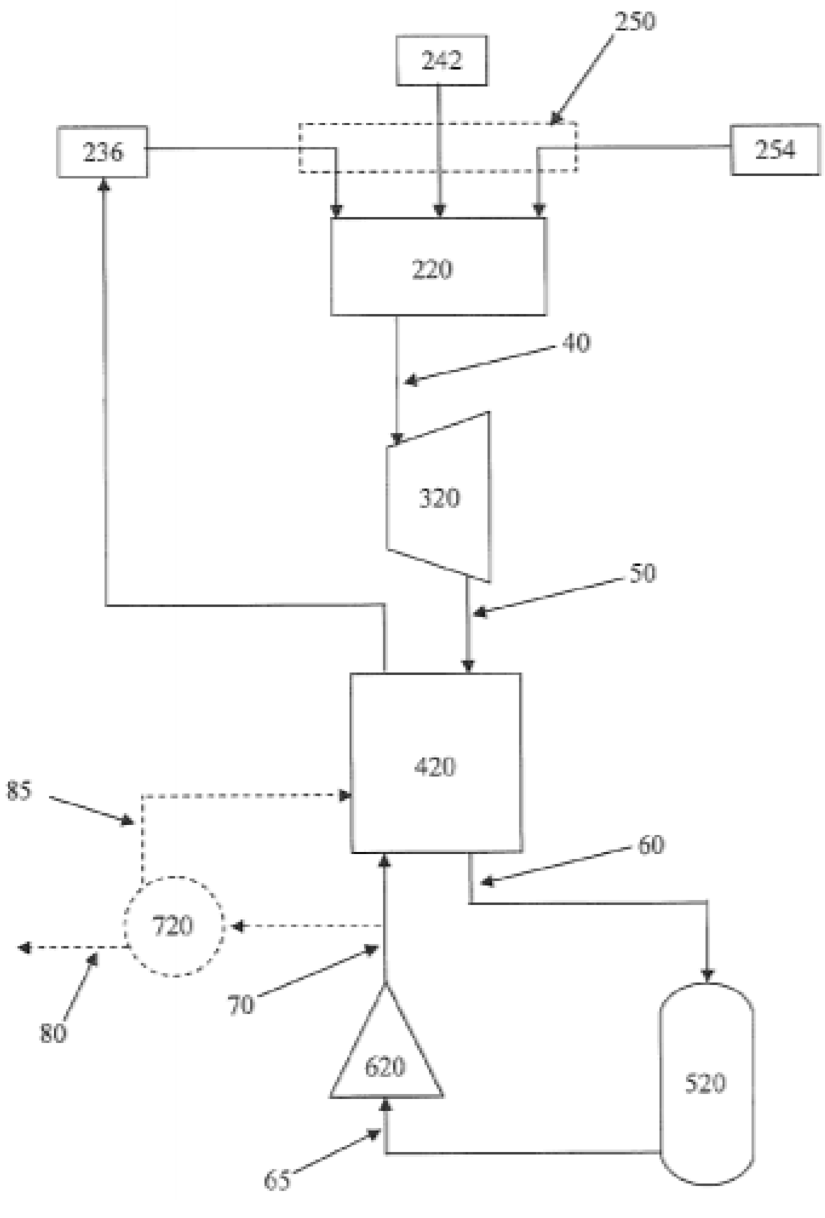

Figure 12.1: Example flow diagram for the Allam cycle, borrowed from USA Patent 8,596,075 B2 [11].

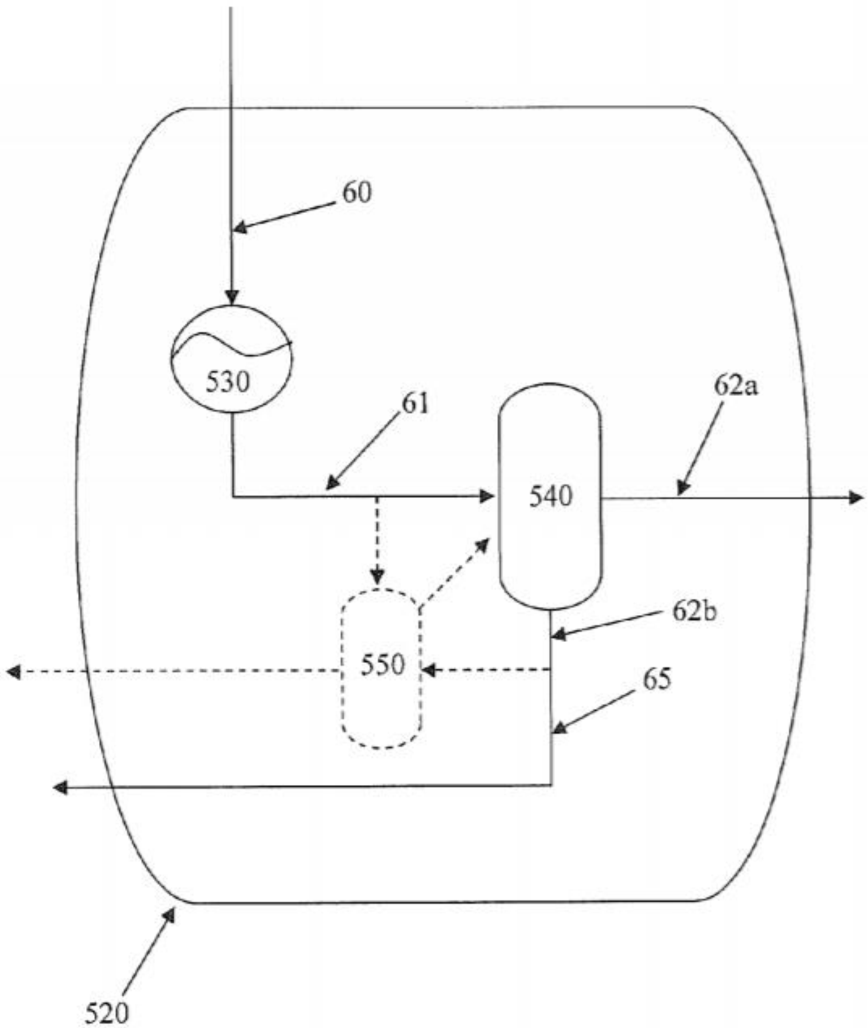

Figure 12.2: More detailed diagram of separation unit (520) from USA Patent 8,596,075 B2. The water separation unit (540) separates the water (62a) from the recycled CO_2 stream (62b) [11].

Preliminary Process Synthesis

13.1. Primary Synthesis Problem

To effectively compare the NGCC and Allam cycle, it is necessary to define where equal boundary conditions can be deployed. Figure 13.1 illustrates the primary synthesis problem for all three cases: to generate 300 MW of electricity from natural gas and air feedstock. Cases 2 and 3 also produce liquid CO_2 at 99% purity as a byproduct. To keep costing consistent and an equivalent output for cases 2 and 3, there is a net power of 322 MW in case 1, and the power requirement for CO_2 separation and compression results in 300 MW of net power in case 2. This allows for a better representation of material balances and costing data between cases 1 and 2, and a less than 10% difference is assumed to not account for a significant economies of scale advantage for case 1.

Natural gas pipeline conditions and costs were equal for both the NGCC and Allam cycle, according to the conditions specified by NETL [12]. Downstream electricity transmission and distribution can also be assumed to be independent of powerplant operations. As a consequence, the sales price of electricity is adjusted to only reflect power generation.

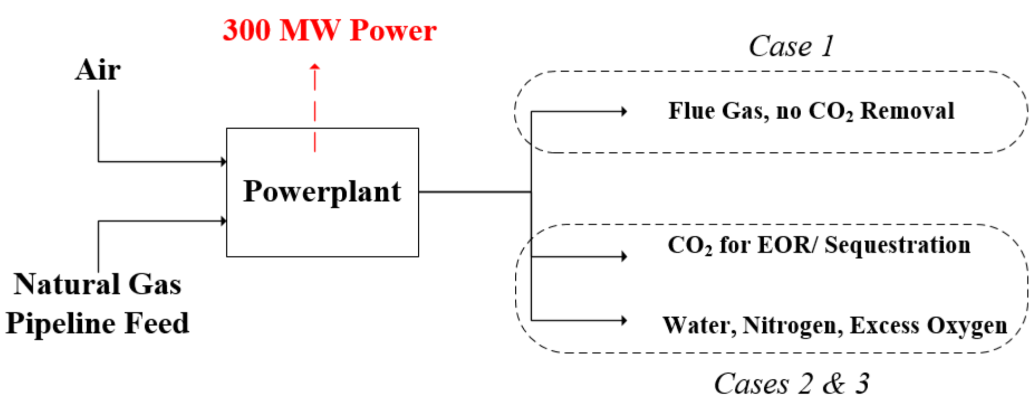

Figure 13.1: Primary Synthesis Problem for Cases 1, 2, and 3

13.2. NGCC Preliminary Process Synthesis

The natural gas-fired combined cycle (NGCC) is a well-established technology. The process relies on a combined Brayton and Rankine cycle. Figure 13.2 in Section 13.4 shows the block flow diagram for the NGCC, with the additional amine scrubbing unit considered in case 2.

In the Brayton cycle, or traditional simple cycle, air and natural gas are compressed to specified combustion pressures. Then, natural gas and oxygen combust, and the high pressure, high temperature gas is expanded to produce power in a gas turbine.

In a simple cycle, the flue gas from the turbine is vented to the atmosphere. However, in the combined cycle, the heat from the turbine exhaust generates steam in a heat recovery steam generator (HRSG), which subsequently produces power in a steam turbine. The steam exiting the turbine is condensed, pumped, and recycled to the HRSG.

The flue gas exiting the HRSG can be vented to the atmosphere (case 1) or treated in a post-combustion CO_2 separation process (case 2). The most common post-combustion technology used in powerplants is an amine scrubbing unit. For the purposes of this analysis, the amine scrubbing unit is treated as a black-box, and the energy and cost requirements from the NETL [13] are used to calculate performance and investment metrics.

Net power from the combined cycle is calculated by subtracting the power required to run the compressors, pumps, and amine scrubbing unit from the gross output of the gas and steam turbines. While there are little degrees of freedom in the general process flow diagram, the various compression and expansion ratios, as well as the downstream tradeoffs in producing steam must be considered. For example, the outlet pressure from the gas turbine was initially assumed to be at atmospheric pressure, but it was later changed to roughly 10 psig to optimally produce power in the Rankine cycle.

13.3. Allam Cycle Preliminary Process Synthesis

The primary capital and energy requirements for post-combustion capture in case 2 are due to the large volume of flue gas that must be processed and compressed from near ambient conditions. Oxyfuel combustion, where inert nitrogen gas is separated in an air separation unit (ASU) before combustion, can reduce the volume of flue gas that must be processed. However, the lack of nitrogen which typically acts as a diluent leads to high adiabatic flame temperatures.

The Allam cycle utilizes oxyfuel combustion, and uses a recycled, supercritical CO_2 (sCO_2) stream to lower the adiabatic flame temperature. According to Fernandes et al. [14], the sCO_2 also reduces the corrosion effect and liquid-like density has lower associated machinery costs. The preliminary block flow diagram, derived from the Allam cycle patent [11], is shown in Figure 13.3 of Section 13.4.

While compression, combustion, and heat exchange in the recuperator are relatively fixed upstream steps, there are larger degrees of freedom in the separation, recycle fraction, and compression or pumping stages. The primary variables analyzed were the molar fraction of oxygen mixed with sCO_2, recycled sCO_2 flow rate, and various operations (i.e., refrigeration vs. adiabatic valve) to cool the flue gas so that water could be condensed to produce CO_2 at pipeline specifications.

The integrated ASU plays a large role in capital and energy requirements. While high purity oxygen at a pressure equal to that of the recycled sCO_2 stream is the desired product of the ASU, there is an opportunity for heat integration from the intercoolers in the air compressors. The fundamental components of cryogenic distillation are a main air compressor (MAC), cryogenic heat exchanger, and cryogenic distillation column. The distillation tower was modelled as two separate columns, a high pressure column (HPC) and low pressure column (LPC). In an actual ASU, there exists one column where the condenser duty of the HPC is equal to the reboiler duty of the LPC, and the column is kept at cryogenic temperatures in a large 'cold box.'

Initially, 95% pure oxygen was produced, brought to ambient conditions in the cryogenic heat exchanger, compressed to sCO_2 pressure, and fed to the Allam cycle. After further analysis, it was realized that oxygen would need to be produced at higher concentrations to meet pipeline CO_2 specifications for inert nitrogen. Also, the compressed gaseous oxygen (GOX) cycle was substituted with a pumped liquid oxygen (LOX) cycle. Pumped LOX cycles require an additional booster air compressor (BAC) for part of the inlet air in order to boil the high-pressure LOX stream leaving the LPC and oxygen pump.

13.4. Block Flow Diagram

Figures 13.2 and 13.3 show the preliminary block flow diagrams for the NGCC (cases 1 and 2) and Allam cycle (case 3), respectively.

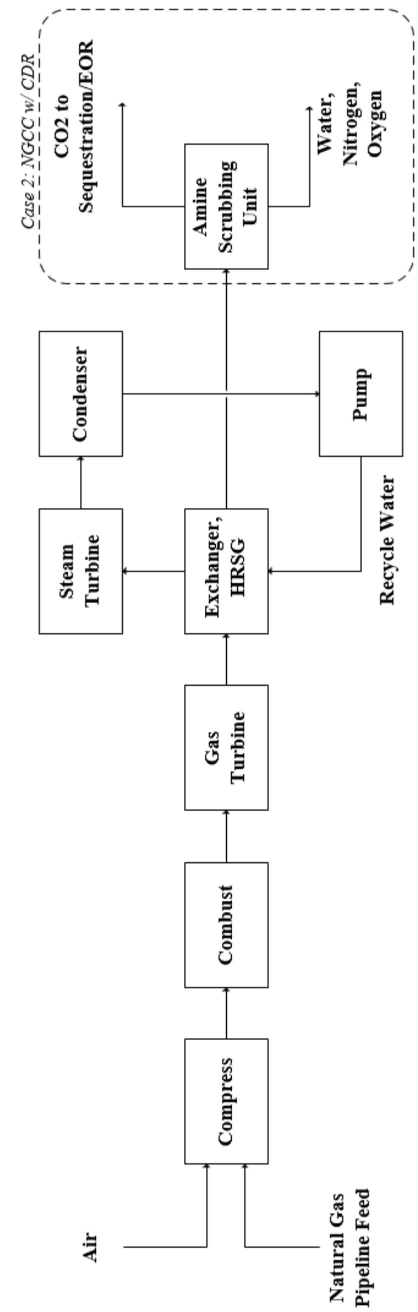

Figure 13.2: Block flow diagram for NGCC (Case 1) and NGCC with CDR (case 2)

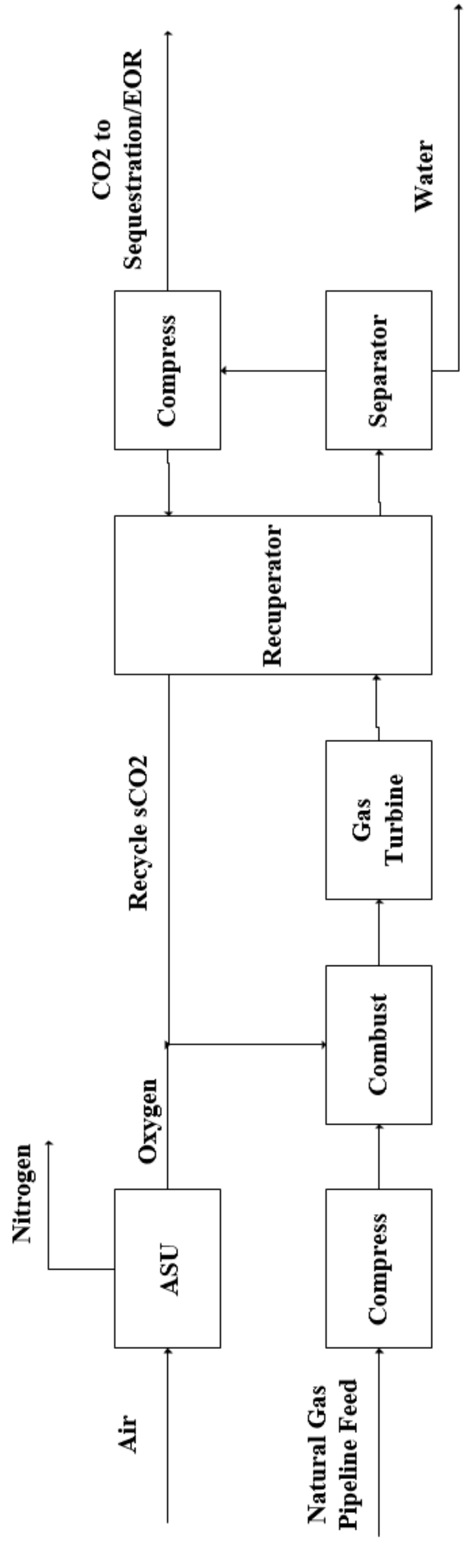

Figure 13.3: Block Flow diagram for the Allam Cycle with integrated ASU (Case 3)

13.5. Modelling Assumptions

The three cases were modelled in Aspen Plus. The NGCC and ASU were modeled with the Peng-Robinson equation of state, as recommended by industrial consultants. The Allam cycle was modeled with the SRK equation of state, as specified in the reference paper [14] in the project assignment. Fernandes et al. [14] noted that although Peng-Robinson would also work, SRK is a better predictor of the CO_2-O_2 mixture experimental density.

Natural gas was assumed to be 100% methane and air was assumed to be 79% nitrogen and 21% oxygen. In a real powerplant, natural gas is roughly 92% methane with the balance consisting of additional hydrocarbons and a small amount of inert N_2 and other gases. However, the heating value efficiency is the main operating parameter, and as long as a conversion from the heating value of methane to that of natural gas is made, the assumption should not significantly impact the comparative analysis. Furthermore, 99% CO_2 was produced in cases 2 and 3, but pipeline purity specs are lower, so an additional one or two percent of inert gases will not affect the ability to receive the CO_2 tax credit.

Assembly of Database

14.1. Carbon Dioxide Phase Diagram

A supercritical fluid exists above the critical point, where liquid and gas phases are indistinguishable. The Allam cycle relies on a supercritical CO_2 working fluid, and a purge stream is cooled for liquid transport to balance the additional CO_2 formed in combustion. Figure 14.1 shows the phase diagram for CO_2, including the liquid transport pipeline region, from [8]. As shown in Figure 14.1, pipeline transportation takes place above the critical pressure of 7.38 MPa, or 1069 psi. Most pipelines operate around 11-13 MPa, so a midpoint of 12 MPa, or 1726 psig, was chosen for the NGCC with CDR and Allam cycle products.

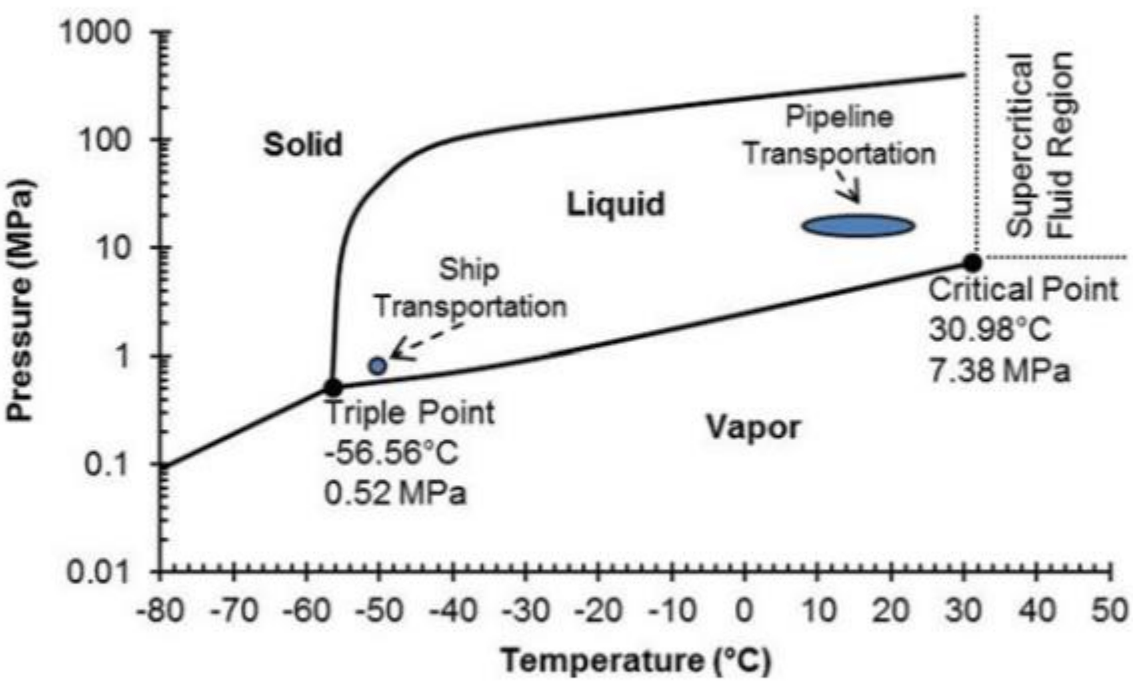

Figure 14.1: Phase Diagram for CO_2, including liquid Pipeline Transportation Pressure and Temperature, from [8]

14.2. Heating Values and Natural Gas Price

Natural gas is priced in terms of MMBtu on a higher heating value (HHV) basis. The HHV of a fuel is the energy produced from combustion, or heat of reaction, plus the energy that is produced from bringing water vapor to liquid at ambient conditions. The lower heating value (LHV) is the reaction heat with water vapor as the product.

In both the NGCC and Allam cycle Aspen Plus models, it is assumed natural gas is 100% methane and completely reacted:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

The heat of reaction calculated by Aspen Plus is 50.0 MJ/kg, which corresponds to the LHV. Aspen Plus also calculates 85.99 kJ are required to condense 2 moles of water, corresponding to 5.4 MJ per kg of methane reacted. Thus, the HHV calculated by Aspen Plus is 55.4 MJ/kg.

Table 14.1 shows HHV and LHV for methane and natural gas from [15]. While English units are standard for pricing (MMBtu), power is typically reported in MW, so metric units are shown in table 14.1(MJ/kg).

Table 14.1: Heating values for Methane and Natural Gas, from [15]

Fuel	HHV	LHV
Methane	55.4 MJ/kg	50 MJ/kg
Natural Gas	45.4 MJ/kg	41 MJ/kg

Values in Table 14.1, supported by thermodynamic values in Aspen Plus, are used to calculate the natural gas requirement from the HHV efficiency in the NGCC and Allam cycle. After determining the heat required from natural gas, the cost can be calculated using the Henry Hub price in $/MMBtu. As of April 12, 2021, when the profitability analysis was conducted, the price of natural gas was $2.50/MMBtu. Figure 14.2 shows historical and projected Henry Hub spot prices from the EIA [16]. Despite historical volatility in the market, the supply and demand dynamics are expected to remain stable in the more mature market, and as such, the price will gradually increase in line with electricity prices and inflation. Because the profitability analyses between all three cases have similar sensitivities to electricity and natural gas margins, a constant price of natural gas and electricity was used. Using current trading prices and the 'Reference' case of Figure 14.2, a constant price of $2.60/MMBtu was assumed for the cash flow analysis.

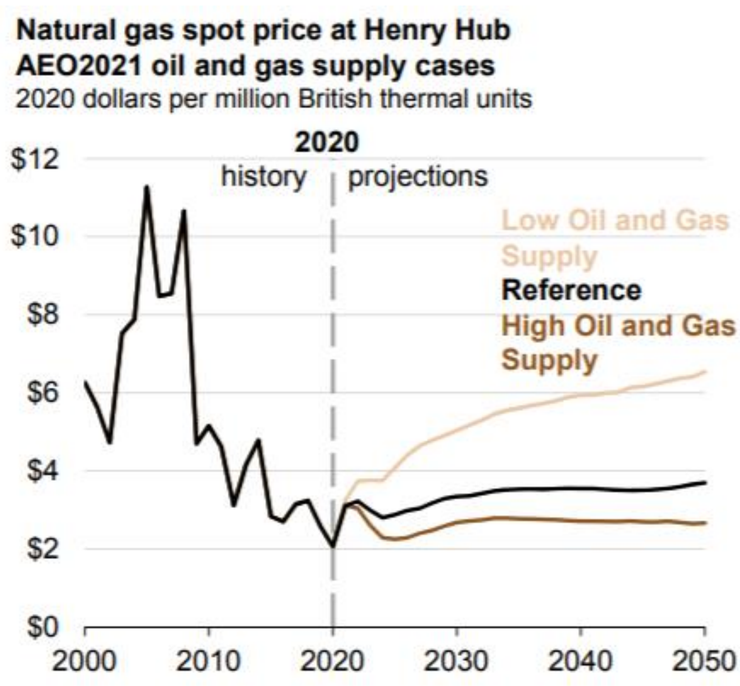

Figure 14.2: Historical and Projected Henry Hub Spot Price, from EIA [16]

14.3. Selling Price for Electricity and CO_2

The primary components of electricity sales prices are generation, transmission, and distribution. Since each case analyzes the associated costs of generation, the sales price must also be assumed to be from generation. Figure 14.3 shows the projected price of electricity in the EIA's "Annual Energy Outlook 2021" [17]. The price of generation is projected to rise from 6.2 cents per kW-hr in 2021 to 8.0 cents per kW-hr in 2044, the final year of operations for each powerplant. As described in Section 14.2, there is greater sensitivity to the CO_2 byproduct credit than the electricity and natural gas margin, so a constant electricity generation sales price was assumed. In line with current trading prices and the trend of Figure 14.3, a constant price of $0.06/kW-hr, or $60/MW-hr, was assumed for the cash flow analysis.

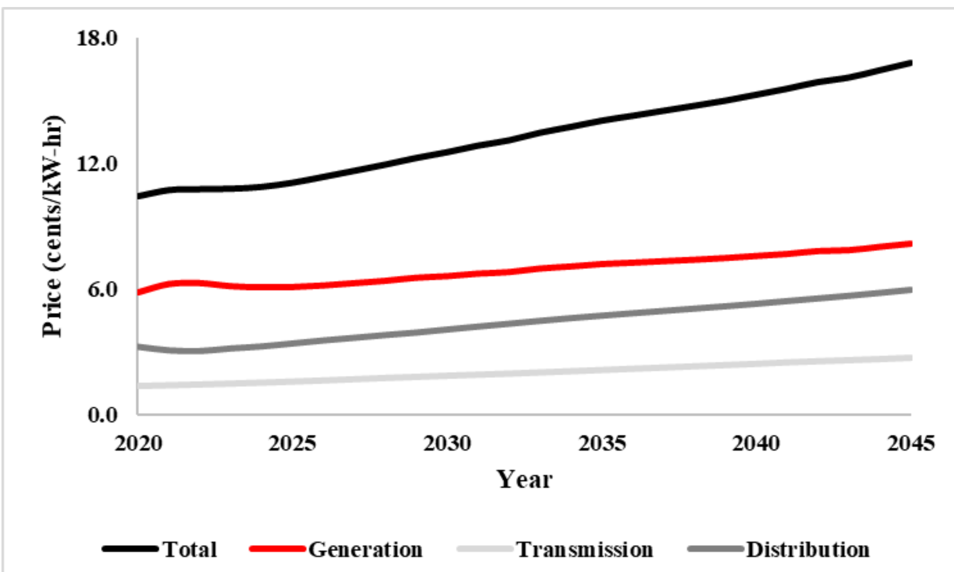

Figure 14.3: Projected price of electricity and its components (cents per kW-hr). Data from EIA's "Annual Energy Outlook 2021" [17].

Process Flow Diagrams and Material Balance

15.1. NGCC PFD and Material Balance

Table 15.1: Stream Information for NGCC (case 1) and NGCC with CDR (case2)

Stream	101	102	103	104	105	106	107	108
Temperature (F)	70	1173	100	141	2491	1174	400	854
Pressure (psig)	0	585	450	585	585	10	10	400
Molar Vapor Fraction	1	1	1	1	1	1	1	1
Mass Flows (tons/hr)	3217	3217	63	63	3280	3280	3280	483
Mole Flows (lbmol/hr)	222984	222984	7846	7846	230830	230830	230830	53610
--Oxygen	0.21	0.21	0.00	0.00	0.13	0.13	0.13	0.00
--Nitrogen	0.79	0.79	0.00	0.00	0.76	0.76	0.76	0.00
--Methane	0.00	0.00	1.00	1.00	0.00	0.00	0.00	0.00
--Water	0.00	0.00	0.00	0.00	0.07	0.07	0.07	1.00
--Carbon Dioxide	0.00	0.00	0.00	0.00	0.03	0.03	0.03	0.00

Stream	109	110	111	112	113	114	115
				streams 112-115 for case 2 only			
Temperature (F)	182	100	100	86	86	100	80
Pressure (psig)	-8	-8	400	10	10	1731	1726
Molar Vapor Fraction	1	0	0	1	1	1	0
Mass Flows (tons/hr)	483	483	483	3123	157	157	157
Mole Flows (lbmol/hr)	53610	53610	53610	223689	7141	7141	7141
--Oxygen	0.00	0.00	0.00	0.14	0.00	0.00	0.00
--Nitrogen	0.00	0.00	0.00	0.79	0.01	0.01	0.01
--Methane	0.00	0.00	0.00	0.00	0.00	0.00	0.00
--Water	1.00	1.00	1.00	0.07	0.00	0.00	0.00
--Carbon Dioxide	0.00	0.00	0.00	0.00	0.99	0.99	0.99

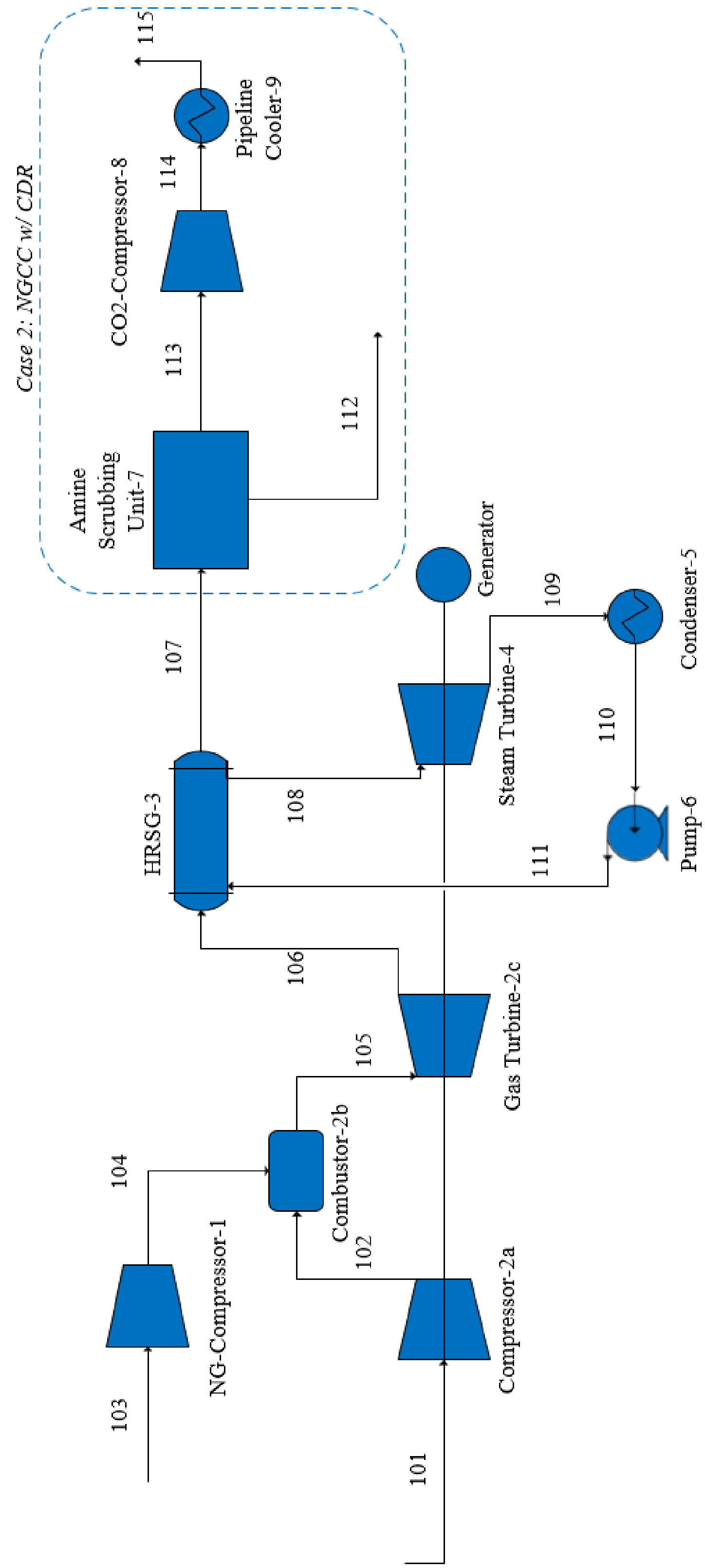

Figure 15.1: PFD for NGCC (Case 1) and NGCC with CDR (case 2)

15.2. Allam Cycle with Integrated ASU PFD

Figure 15.2 shows the PFD for the Allam cycle with integrated ASU. Figure 15.3 and Table 15.2 provide stream information on just the Allam cycle, and Figure 15.4 and Table 15.3 provide stream information on just the ASU.

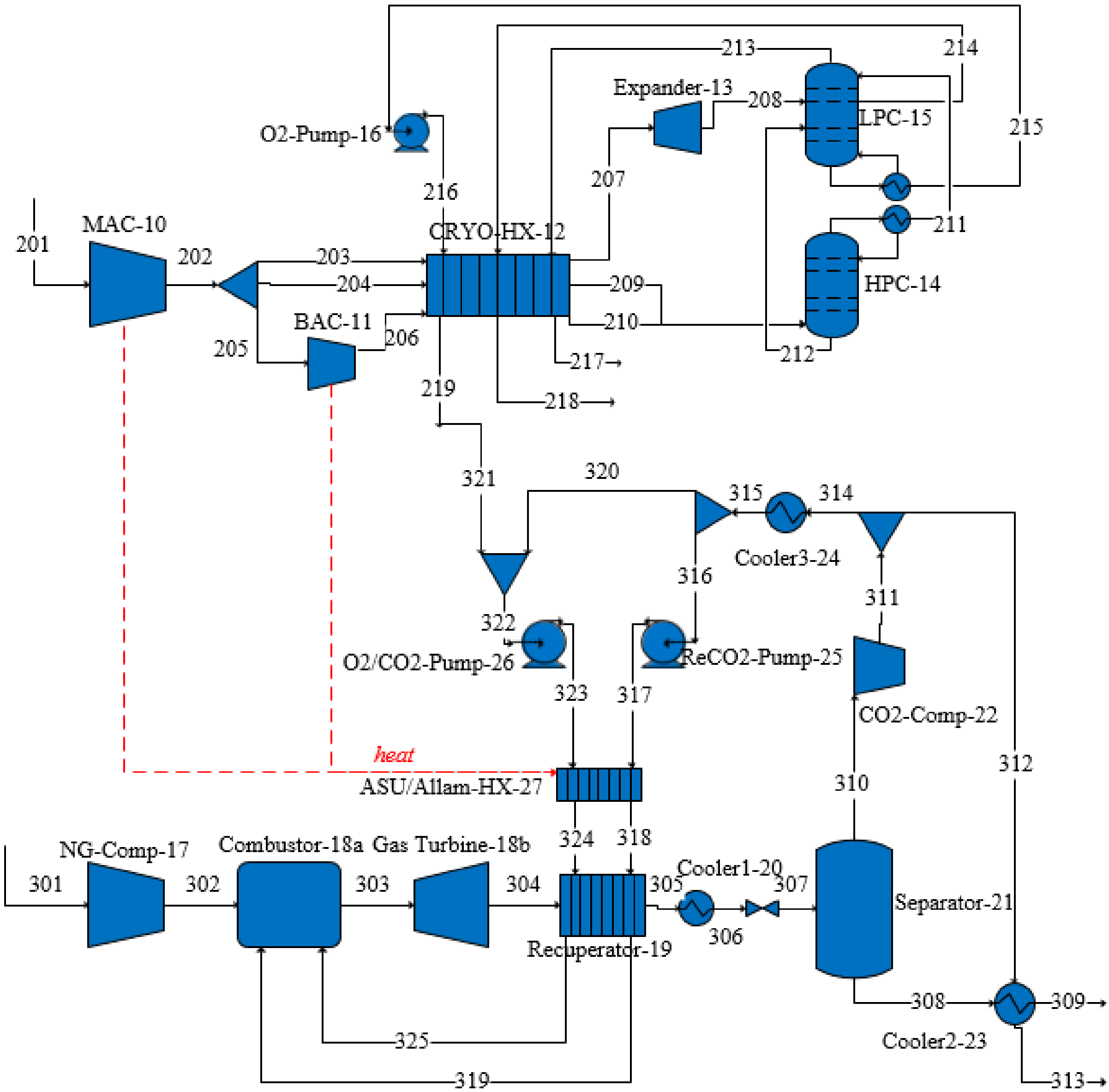

Figure 15.2: PFD for Allam cycle with integrated ASU (case 3)

15.3. Allam Cycle PFD and Material Balance

Table 15.2: Stream Table for Allam cycle (case 3)

Stream	**301**	**302**	**303**	**304**	**305**	**306**	**307**	**308**	**309**	**310**	**311**	**312**
Temperature (F)	100	293	2062	1421	188	92	71	71	88	71	100	100
Pressure (psig)	450	4336	4336	420	415	415	232	232	232	232	1731	1731
Molar Vapor Fraction	1	1	1	1	0.96	0.94	0.94	0	0	1	0	0
Mass Flows (tons/hr)	62	62	5022	5022	5022	5022	5022	139	139	4882	4882	171
Mole Flows (lbmol/hr)	7726	7726	238329	238329	238329	238329	238329	15455	15455	222874	222874	7801
--Methane	1	1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
--Carbon Dioxide	0	0	0.92	0.92	0.92	0.92	0.92	0.00	0.00	0.99	0.99	0.99
--Oxygen	0	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
--Nitrogen	0	0	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.01	0.01	0.01
--Water	0	0	0.07	0.07	0.07	0.07	0.07	1.00	1.00	0.00	0.00	0.00
Stream		**314**	**315**	**316**	**317**	**318**	**319**	**320**	**321**	**322**	**323**	**324**
Temperature (F)		100	95	95	149	170	1270	95	90	75	144	170
Pressure (psig)		1731	1731	1731	4341	4341	4336	1731	1726	1726	4341	4341
Molar Vapor Fraction		0	0	0	0	0	1	0	1	0	0	1
Mass Flows (tons/hr)		4711	4711	2795	2795	2795	2795	1917	248	2165	2165	2165
Mole Flows (lbmol/hr)		215073	215073	127584	127584	127584	127584	87489	15530	103019	103019	103019
--Methane		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
--Carbon Dioxide		0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.00	0.84	0.84	0.84
--Oxygen		0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.15	0.15	0.15
--Nitrogen		0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
--Water		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

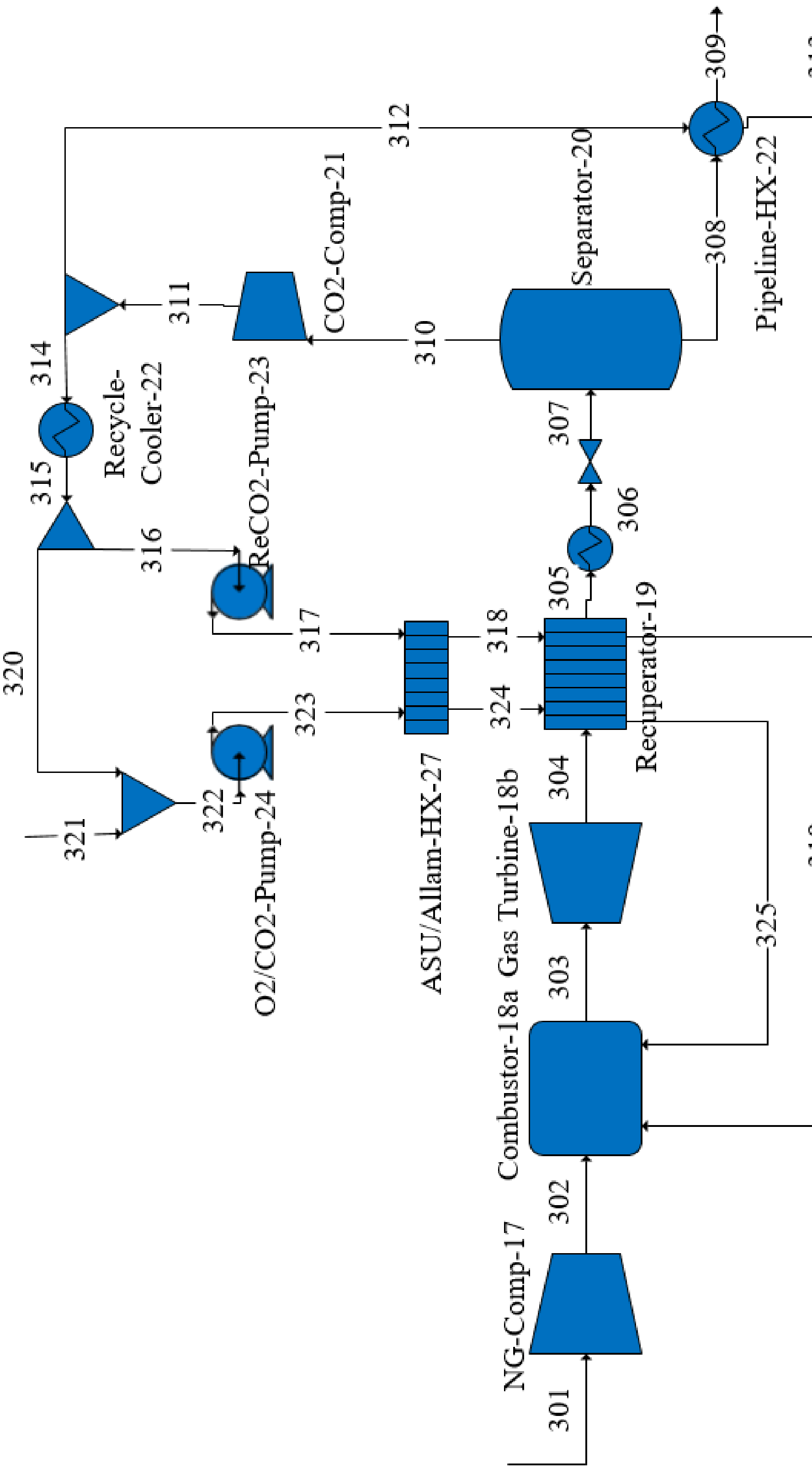

Figure 15.3: PFD for Allam Cycle

15.4. ASU PFD and Material Balance

Table 15.3: Stream Table for ASU

Stream	201	202	203	204	205	206	207	208	209	210
Temperature (F)	70	100	100	100	100	100	-150	-236	-234	-234
Pressure (psig)	0	82	82	82	82	1035	77	11	77	1035
Molar Vapor Fraction	1	1	1	1	1	1	1	1	1	0
Mass Flows (tons/hr)	1275	1275	128	472	676	676	128	128	472	676
Mole Flows (lbmol/hr)	88404	88404	8840	32710	46854	46854	8840	8840	32710	46854
--Nitrogen	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79
--Oxygen	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21

Stream	211	212	213	214	215	216	217	218	219
Temperature (F)	-288	-281	-313	-306	-286	-278	90	90	90
Pressure (psig)	65	70	8	10	13	1731	8	10	1726
Molar Vapor Fraction	0	0	1	1	0	0	1	1	1
Mass Flows (tons/hr)	382	766	810	217	248	248	810	217	248
Mole Flows (lbmol/hr)	27224	52340	57729	15146	15530	15530	57729	15146	15530
--Nitrogen	0.99	0.69	0.99	0.83	0.005	0.005	0.99	0.83	0.005
--Oxygen	0.01	0.31	0.01	0.17	0.995	0.995	0.01	0.17	0.995

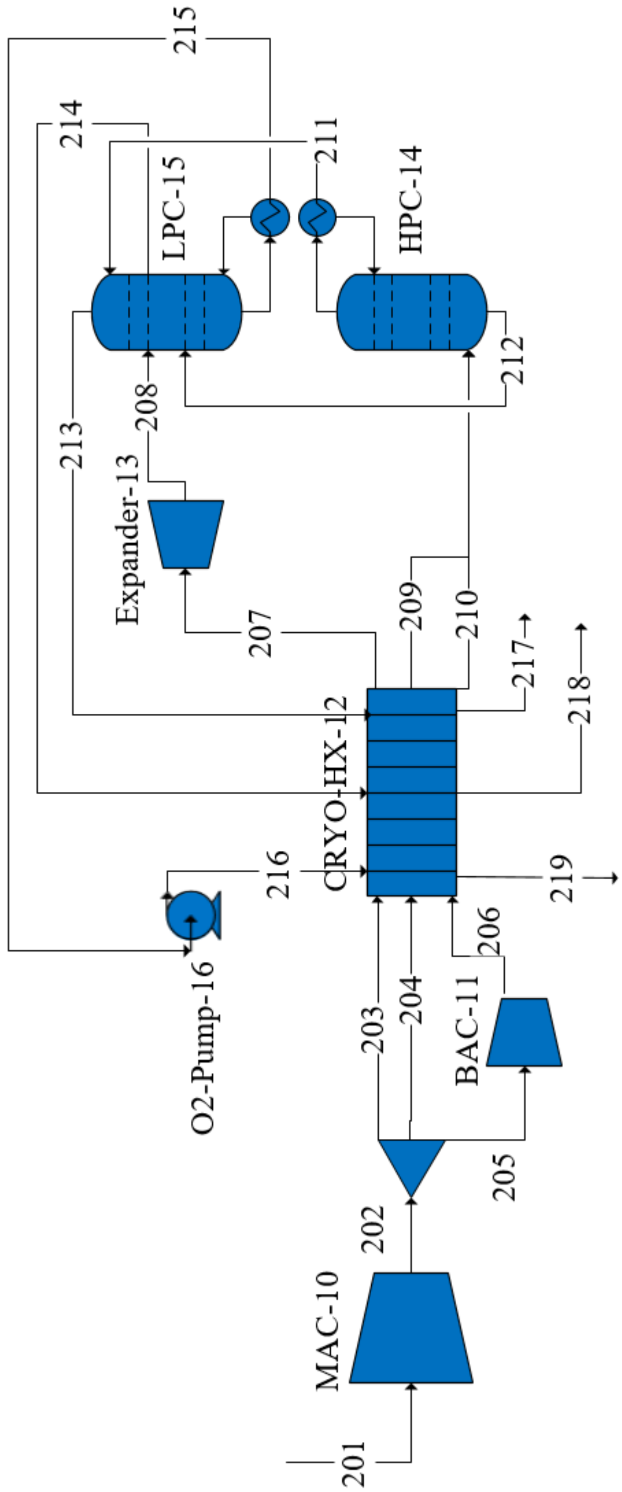

Figure 15.4: PFD for Air Separation Unit (ASU)

Process Descriptions

Sections 16.1-16.2 describe the 3 cases: NGCC, NGCC with CDR, and the Allam cycle. Stream and block IDs are referenced according to the figures in Section 15. For example, stream 100 and block 10 would be referenced as (s100) and (B10), respectively.

16.1. NGCC Process Description

16.1.1. Brayton Cycle

Figure 15.1 shows the PFD for cases 1 and 2, standard NGCC and NGCC with carbon dioxide removal (CDR). Air (s101) is compressed from atmospheric pressure to 585 psig (s102) in an adiabatic, single stage, compressor (B2a). Natural gas (s103) is compressed in (B1) to the same outlet pressure (s104), but from pipeline conditions of 100^{o}F and 450 psig, as specified in [12]. Inlet air is assumed to be at 70^{o}F in the U.S. Gulf Coast. The same inlet air and natural gas conditions were used in the Allam cycle.

Compressed air and natural gas are fed to the combustor (B2b), which also operates at 585 psig and is assumed to be adiabatic. The outlet stream (s105) enters the gas turbine (B2c) at 2491^{o}F. Excess air was required to keep this adiabatic flame temperature below the maximum value of 2600 ^{o}F specified in the most recent GE turbine technology. The gas turbine expands the combustion outlet to 10 psig and 1174 ^{o}F (s106), producing power to run a generator.

In actual plants, the compressor, combustion chamber, and gas turbine are designed as one piece of equipment, all run on the same shaft. The natural gas compressor is a separate piece of equipment that is assumed to operate at a polytropic efficiency of 85% and requires 0.8 MW of power. The net power produced from the gas turbine, minus the power required to compress air, is 232.5 MW. For a net output that large, it was advised to run two turbines in parallel, each with 116.3 MW. The air compressor and gas turbine were assumed to operate at an isentropic efficiency of 85%.

16.1.2. Rankine Cycle

The gas turbine exhaust (s106) is at 1174°F, and thus, can produce steam in the heat recovery steam generator (HRSG, B3). The HRSG was designed as a shell and tube heat exchanger, with the flue gas exiting at 400 °F. 1965 gpm of boiler-feed water is fed (s111) at 400 psig and 100°F on the shell side and is vaporized to 854°F (s108). The generated steam expands in a steam turbine (B4), which produces electricity in a generator. The exhaust of the steam turbine (s109) is 7.2 psia, or -7.5 psig, as specified by project author Adam Brostow. The vapor is totally condensed with cooling water to 100 °F (s110). The condenser (B5) was modelled as a shell and tube HX and requires 174,880 gpm of cooling water on the tube side. The condensed water is pumped by (B6) to 400 psig (s111) and cycled back through the HRSG.

With an assumed isentropic efficiency of 85%, the steam turbine produces 91 MW of power. The water pump requires 0.4 MW of power, resulting in 90.6 MW of net power in the Rankine cycle.

16.1.3. NGCC with Carbon Dioxide Removal (CDR)

In case 1, the flue gas (s107) leaving the HRSG (B3) is vented to the atmosphere. In case 2, the flue gas is treated in a CDR unit (B7). While the CDR system is treated as a black box in this analysis, the capital, variable, and energy costs are well documented by the NETL [13] for the Shell Cansolv system. Amine-based scrubbing units, such as the Cansolv technology, are standard for post-combustion capture, and the process flow diagram from NETL is included in Appendix 28.8.

The CDR system is capable of recovering 90% of the CO_2 in the flue gas at a 99% purity. The treated CO_2 stream (s113) is pressurized from 10 psig to 1731 psig (s114) in a four-stage, intercooled and after cooled centrifugal compressor (B8), with equal compression ratios. The CO_2 compressor is assumed to have a polytropic efficiency of 85% with 5 psi pressure drop in the intercoolers and is driven by the steam turbine. The discharge stream (s114) is cooled in (B9) to 80 ^oF with chilled water at 40 ^oF. The pipeline CO_2 cooler has a pressure drop of 5 psi and a total cooling duty of -4.97 MMBtu/hr. The exiting liquid CO_2 steam (s115) is at 80 ^oF and 1726 psig, as specified in Section 14, 'Assembly of Databases.' As shown in Appendix 28.8, the amine scrubbing unit requires 9.7 MW of power. Much of the power requirement is to generate steam for solvent regeneration, and the remaining power runs the blower fan in the column. After separation, the CO_2 compressor requires an additional 12.6 MW of power.

16.2. Allam Cycle Process Description

The PFD for case 3, the Allam cycle with an integrated air separation unit (ASU), is shown in Figure 15.2. High purity oxygen and heat from the air compressors are the two feedstocks from the ASU to the Allam cycle.

16.2.1. Allam Cycle

Figure 15.3 shows the PFD for the Allam cycle. The creators of the Allam cycle [10] specified a combustion pressure of 300 bar, or 4336 psig, and a compression ratio of 10 in the gas turbine. While downstream conditions and processes are adjusted to agree with the boundary conditions, performance assumptions, and equipment design specs of this analysis, the turbine inlet and outlet pressures are assumed to be fixed at 4336 psig and 420 psig, respectively.

Natural gas (s301) is compressed from 450 psig, as is assumed in the NGCC, to 4336 psig in a two-stage, centrifugal compressor (B17) with equal compression ratios and one intercooler. There is no aftercooler since the heat is used in the turbine. A polytropic efficiency of 85% and a 5-psi drop was assumed, consistent with the NGCC and other intercooled compressors. The compressed natural gas stream (s302) is fed to the combustor (B18a) with a recycled supercritical CO_2 stream (s319) and stream (s325) that contains supercritical CO_2 and oxygen in stoichiometric proportion to methane in (s301). The combustor is assumed to be adiabatic as in the NGCC, and the outlet stream (s303) is 4336 psig and 2062 ^oF.

The combustion outlet produces power in a gas turbine (B18b) with a compression ratio of 10. The turbine outlet (s304) at 420 psig and 1421 ^oF heats the two recycle streams (s324, s318) in the recuperative heat exchanger (B19) and is cooled to 188 ^oF (s305), with an associated pressure drop of 5-psi. Recuperators used in this application are generally printed circuit heat exchangers (PCHEs). According to Heatric [23], a large supplier of PCHEs, they utilize a 'diffusion-bonding' process to eliminate welds, joints, and points of failure in the exchanger core. PCHEs are typically lighter than a shell and tube exchanger and require less piping and supporting equipment. Images of PCHEs from Heatric are included in Appendix 28.10.

The CO_2 and water separator (B20) is designed as a flash vessel at 71°F. The stream (s305) exiting the recuperator is cooled to ambient conditions (s306) with cooling water in cooler-1 (B20). To avoid refrigeration, an isenthalpic valve reduces the pressure of (s306) to 232 psig, which leads to a temperature of 71 °F in (s307). Additional electricity can be produced if the valve was replaced with a low-pressure turbine generator, but the tradeoff is a higher capital cost. Due to a compression ratio of only 2, the valve was decided to be the more economical decision.

The flash vessel (B21) condenses water at 71 °F (s308) and CO_2 vapor exits the top (s310). The water at 70°F is used to cool the supercritical CO_2 stream (s312) to liquid pipeline conditions of 80 °F (s313) in cooler-2 (B23). The wastewater (s309) exits (B23) at 88 °F.

CO_2 vapor (s310) from the separator is compressed to 1731 psig (s311) in a four-stage, centrifugal compressor (B22) with 5-psi drop in the intercoolers. The CO_2 compressor is assumed to have a polytropic efficiency of 85%, consistent with the NGCC, and four compressors are run in parallel due to the horsepower restriction for a single compressor. The 142.3 MW power requirement can be reduced if refrigeration is used and (s306) is maintained at 415 psig. However, this would also lead to refrigeration costs and a larger pressure vessel (B20) investment due to the increased thickness required. Ultimately, the decision to use a valve favored lower capital investment despite the consequence of slightly lower performance.

After compression, 96.5% of the supercritical CO_2 stream (s311) is recycled (s314), and the remaining 3.5% is purged (s312) to balance the additional CO_2 produced from combustion of methane. The split fraction was adjusted from an initial value of 97% to 96.5% to produce a desired adiabatic flame temperature in the combustor. The purged supercritical CO_2 is cooled in (B23) to a liquid at 80 °F from the water (s308) leaving the separator (B21) at 71 °F. Liquid CO_2 (s313) is at 99% purity and 1726 psig, as specified in Section 13 and for the NGCC with CDR.

After cooling in (B24), the recycled CO_2 stream (s315) is split into two streams (s316, s320). The split fraction was calculated such that the resultant mixed stream (s322) from the O_2 (s321) and split stream (s320) would be 15% oxygen. While [14] specifies a molar fraction of 25% oxygen, the fraction was reduced so that the downstream pump (B26) would be within vendor specifications for pressure head.

The two recycled streams (s316, s322) are pumped from 1726 psig to 4341 psig in (B25, B26). The pump outlet streams (s317, s323) are then preheated in (B27) with heat from the air compressors in the ASU. It was assumed that compressed air at 180 °F, with a warm side delta T of 10 °F, can heat the two streams to 170 °F. This assumption was validated and is shown in the full Aspen stream report and file included with this report. The outlet streams (s318, s324) from the ASU preheater are then heated to 1270 °F in the recuperator (B19), with an associated pressure drop of 5 psi. The heated recycle streams (s319, s325) are fed to the combustor at 4336 psig and 1270 °F to complete the cycle.

16.2.2. ASU

Figure 15.4 shows the PFD for the ASU. Air is compressed from ambient conditions (s201) in the main air compressor (MAC, B10) to 82 psig. The MAC is a three-stage, centrifugal compressor. The polytropic efficiency was assumed to be 85%, consistent with the NGCC and Allam cycle, and a pressure drop of 2 psi was assumed due to the lower pressure outputs. Due to flow rate restrictions, four compressors are run in parallel, with 18.6 MW required for each.

Ten percent of the compressed air (s203) is fed to the expander and low pressure column (LPC), as specified by project author Adam Brostow. Of the remaining 90%, 59% is compressed in the booster air compressor (BAC, B11) to provide sufficient energy to boil the pumped liquid oxygen (LOX) stream (s216). The outlet pressure of the BAC was specified by [18]. The BAC is a four-stage centrifugal compressor with 85% polytropic efficiency and 5-psi drop in the intercoolers. As described in Section 16.2.1, the intercoolers of the MAC and BAC reject heat to the recycled streams in the Allam cycle in (B27). Because the hot inlet streams from the Allam cycle are already above 140 ^oF, there is an additional cooling water requirement of 20,000 gpm to cool the interstage streams of the MAC and BAC to 100 ^oF. The cooling water enters at 90 ^oF and exits at 118 ^oF. Only the final outlet streams are shown in Table 15.3, but the interstage and cooling water streams are included in the full Aspen Plus stream report in Appendix 28.23.

The MAC (B10) product streams (s203, s204) at 82 psig and the BAC outlet stream (s206) at 1035 psig are fed to the cryogenic heat exchanger (B12). A warm side delta T of 10 ^oF and an assumption of no heat leak in the ASU was specified by project author Adam Brostow. The cryogenic heat exchanger is a brazed aluminum, plate-fin heat exchanger modeled as MHEATX in Aspen Plus. Due to the no heat leak assumption, the refrigeration requirement for the ASU accounts for the warm side delta T and is provided by the expander (B13).

The cryogenic heat exchanger cools streams (s203, s204, s206) to -150 ^oF, -234 ^oF, and -234 ^oF, respectively. A 5-psi drop in the heat exchanger is assumed. Then 10% of outlet MAC (s207) is expanded from 77 to 11 psig (s208) and fed to the LPC (B15). The remaining 90% (s209, s210) are fed to the bottom of the HPC (B14). The bottoms of the HPC (s212) is fed to theoretical tray 25 of the LPC, and the distillate of the HPC (s211) is fed to the top of the LPC.

The LPC (B15) has three inlet streams (s208, s211, s212). The LPC distillate (s214) is 99% nitrogen, and the bottoms of the LPC (s215) is 99.5% oxygen. There is a side stream draw off (s214) that is low purity nitrogen. While (s214) can be sold if a customer is nearby, the low purity nitrogen must be vented to the atmosphere.

The HPC and LPC were modeled as two separate columns in Aspen Plus but exist as only one column in real ASUs. Therefore, the condenser duty of the HPC must equal the reboiler duty of the LPC. This specification was met by varying the MAC, BAC, and expander conditions until the duties were equal at 119 MMBtu/hr.

The liquid oxygen from the bottoms (s215) of the LPC is pumped from 13 psig to 1731 psig (s216). The high purity nitrogen (s214), waste (s215), and high-pressure LOX (s216) were heated to 90 ^oF in the cryogenic heat exchanger (B12), with an associated pressure drop of 5-psi. The oxygen stream (s219) is fed to the Allam cycle at 99.5% purity, 90 ^oF, and 1726 psig.

Energy Balance and Utility Requirements

17.1. NGCC Energy Balance and Utility Requirements

Table 17.1 shows the energy balance for the NGCC. Flow work, $\dot{W}$, as commonly shown in energy balance notation, is replaced with the more traditional vocabulary, power, to describe the desired process output. The conservation of energy for the NGCC is as follows:

$$0 = Enthalpy\ Flow\ Out - Enthalpy\ Flow\ In - \dot{W}_{shaft} + \dot{Q}_{condenser}$$

Table 17.1: Energy Balance for the NGCC (Case 1)

	MMBtu/hr	**MW**
Flow Out (s107)	2424	710
Flow In (s101+s103)	263	77
Flow Out - Flow In	**2160**	**633**
Gas Turbine	2600	762
Steam Turbine	310	91
Natural Gas Compressor	-3	-1
Air Compressor	-1807	-529
Pump	-1	-0.4
NET POWER	**1100**	**322**
Condenser Duty	**-1061**	**-311**
Balance	**0**	**0**

The net power produced in case 1 is 322.3 MW. With a methane flow rate of 15.86 kg/s, the HHV efficiency is 36.7%. Utility requirements include cooling water in the condenser and boiler-feed water (bfw) that cycles through the HRSG, steam turbine, condenser, and pump. The condenser is a shell and tube heat exchanger with a cooling water requirement of 174,880 gpm. The HRSG was also modelled as a shell and tube heat exchanger with 1965 gpm of bfw required.

17.2. NGCC with CDR Energy Balance and Utility Requirements

Table 17.2 shows the energy balance for the NGCC with CDR, case 2. The conservation of energy for the NGCC with CDR is as follows:

$$0 = Enthalpy\ Flow\ Out - Enthalpy\ Flow\ In - \dot{W}_{shaft} + \dot{Q}_{net}$$

Table 17.2: Energy Balance for NGCC with CDR (Case 2)

	MMBtu/hr	MW
Flow Out (s112+s115)	3200	938
Flow In (s101+s103)	263	77
Enthalpy Out - Enthalpy In	**2936**	**861**
Gas Turbine	2600	762
Steam Turbine	310	91
Natural Gas Compressor	-3	-1
Air Compressor	-1807	-529
Pump	-1	-0.4
CO2 Compressor	-43	-13
Amine Unit	-33	-10
NET POWER	**1023**	**300**
Condenser Duty	-1061	-311
CDR Cooling	-743	-218
CDR Heat Balance	-33	-10
Cooling Water (Intercoolers)	-71	-21
Refrigeration	-5	-1
Net Heat Flow	**-1913**	**-561**
Balance	**0**	**0**

The net power produced in case 2 is 300 MW. With a methane flow rate of 15.86 kg/s, the HHV efficiency is 34.1%. The HRSG was modelled as a shell and tube heat exchanger with a boiler-feed water flow rate of 1965 gpm, and the condenser was also modelled as a shell and tube heat exchanger with a cooling water flow rate of 174,880 gpm. The power requirement for the amine unit was calculated from [13] and is balanced with a heat input for regeneration of the solvent, as shown in Table 17.2. The cooling water for the CDR is included in the capital investment, and the operating cost for the steam is accounted for in the power requirement. There is an additional cooling water requirement of 71 MMBtu/hr for the CO_2 compressor inter and aftercoolers. Chilled water at 40^{o}F supplies 4.97 MMBtu/hr of cooling to reach the liquid pipeline specifications.

17.3. Allam Cycle Energy Balance and Utility Requirements

Table 17.3 shows the energy balance for the Allam cycle, case 3. The conservation of energy for the Allam cycle is as follows:

$$0 = Enthalpy\ Flow\ Out - Enthalpy\ Flow\ In - \dot{W}_{shaft} + \dot{Q}_{cooling\ water} + \dot{Q}_{ASU\ Integration}$$

Table 17.3: Energy Balance for the Allam Cycle (Case 3)

	MMBtu/hr	**MW**
Flow Out (s309+s321)	3258	955
Flow In (s301+s321)	252	74
Enthalpy Out - Enthalpy In	**3006**	**881**
Turbine	2096	614
Natural Gas Compressor	-26	-7
CO2 Compressor	-486	-142
O2/CO2 Pump	-68	-20
ReCO2 Pump	-76	-22
NET POWER	**1441**	**422**
Cooling Water	**-1680**	**-492**
Heat from ASU	**114**	**34**
Balance	**0**	**0**

The net power produced in the Allam cycle without ASU integration is 422 MW. Subtracting the power requirement of 122 MW, shown in Table 17.4, for the ASU yields a net 300 MW for case 3. With a methane flow rate of 15.62 kg/s, the HHV efficiency for case 3 is 34.7%. The cooling water requirement of 1680 MMBtu/hr accounts for cooling the flue gas leaving the recuperator and all compressor intercoolers and aftercoolers. The heat integration of 114 MMBtu/hr equals the heat flow from the MAC and BAC inter and aftercoolers, also shown in Table 17.4.

17.4. ASU Energy Balance and Utility Requirements

Table 17.4 shows the energy balance for the ASU. The conservation of energy for the Allam cycle is as follows:

$$0 = Enthalpy\ Flow\ Out - Enthalpy\ Flow\ In - \dot{W}_{shaft} + \dot{Q}_{cooling\ water} + \dot{Q}_{Allam\ Cycle\ Integration}$$

Table 17.4: Energy Balance for the ASU

	MMBtu/hr	**MW**
Flow Out (s217+s218+s219)	-1	-0.3
Flow In (s201)	5	1
Enthalpy Out - Enthalpy In	**-6**	**-1.7**
MAC	-254	-74
BAC	-166	-49
Expander	5	1
O2 Pump	-3	-1
NET POWER	**-417**	**-122**
Cooling Water	-297	-87
Heat to Allam Cycle	-114	-34
HPC Condenser	119	35
LPC Reboiler	-119	-35
NET HEAT	**-411**	**-120**
Balance	**0**	**0**

The ASU requires 122 MW of power. As shown in the Allam cycle energy balance, 114 MMBtu/hr of heat is integrated with the Allam cycle recycle streams. The detailed stream report in the Appendix and Aspen Plus files show an additional 20,000 gpm of cooling water at 90 ^{o}F required for the MAC and BAC intercoolers and aftercoolers to reach 100 ^{o}F. The HPC condenser and LPC reboiler duties are equal, as required for the single column design.

Equipment List and Unit Descriptions

18.1. NGCC Equipment List and Unit Descriptions

18.1.1. Natural Gas Compressor

A natural gas compressor is needed to compress the gas to the same pressure as the compressed air. It receives natural gas at pipeline conditions of 465 psig and compresses the gas to 585 psig. It was modeled as a single stage compressor in Aspen Plus, using the ASME method, with a polytropic efficiency of 85%. A carbon steel reciprocating compressor, driven by the gas turbine was assumed for this process. Using the guidelines in Chapter 16 of Seider et al. [19], shown in Appendix 28.1, the equipment purchase cost is $669,000.

18.1.2. Air Compressor, Combustor, and Gas Turbine

The air compressor is a single stage, adiabatic compressor that compresses ambient air at a compression ratio of about 40 to 585 psig. It has an isentropic efficiency of 85%. The air and natural gas are both fed to the adiabatic combustor at a constant pressure of 585 psig, where complete conversion of methane was assumed. The combustion products are then fed into the gas turbine to expand to 10 psig at an isentropic efficiency of 85%. The net power of the gas turbine, minus the air compressor is 232.5 MW. The air compressor, combustor, and gas turbine units are usually combined into one piece of equipment that run on the same shaft. For this process, it is designed as two F-class GE gas turbines in parallel, with costing correlation shown in Appendix 28.2. The equipment purchase cost for each turbine is $35,800,000.

18.1.3. Heat Recovery Steam Generator

The HRSG takes in hot exhaust gas from the gas turbine through the tube side, which has an outer diameter of 0.75 inches and a length of 186 inches. There are 6068 tubes in square pitch, with 1 tube pass. 483 tons/hr of high-pressure, pumped boiler-feed water enters the exchanger though the shell side, which has an inner diameter of 93 inches and an outer diameter of 102.75 inches. There are 12 baffles. In the exchanger, the hot gas vaporizes the water for expansion in the steam turbine. In case 1, the flue gas that leaves the HRSG is vented to the atmosphere but in case 2, this gas is taken up in the amine scrubbing unit to capture 90% of the CO_2 at 99% purity. The HRSG is a shell and tube heat exchanger, and both the shell and tube material are carbon steel. There are 10 exchangers in parallel and 2 in series. The purchase cost is $13,700,000, and the detailed equipment design and cost is included in Appendix 28.3.

18.1.4. Steam Turbine

The steam turbine operates at vacuum conditions to expand vaporized water from 400 psig to -7.5 psig, as specified by project author Adam Brostow. It operates at an isentropic efficiency of 85% and produces 91.0 MW of power. The steam turbine drives the CO_2 compressor in case 2. The equipment purchase cost of $14,600,000 was calculated from the correlation in [12], shown in Appendix 28.4.

18.1.5. Condenser

The condenser is modeled as a shell and tube heat exchanger where both the shell and tube material are carbon steel. The expanded vapor from the steam turbine goes through the shell side, which has an inner diameter of 100 inches and an outer diameter of 101 inches. 43,667 tons/hr of cooling water goes through the tube side, which has a tube diameter of 0.75 inches and a length of 240 inches. There are 8006 tubes in square pitch, with 4 tube passes. There are 6 baffles. In the condenser, cooling water at 86^{o}F condenses the vapor to 100^{o}F at -7.5 psig, the same pressure as the steam turbine. There are 10 heat exchangers in parallel and 1 in series. The equipment purchase cost is $5,400,000, and the detailed equipment design and cost is included in Appendix 28.4.

18.1.6. Pump

The pump pressurizes water from the condenser from -7.5 psig to 400 psig for use in the HRSG. It is a centrifugal pump made of carbon steel. With an assumed efficiency of 85%, the power required is 0.41 MW, provided by an electric motor. Using the guidelines in Chapter 16 of Seider et al. [19], shown in Appendices 28.6 and 28.7, the equipment purchase cost for the pump and electric motor are $211,000 and $65,800, respectively.

18.1.7. Amine Scrubbing Unit

The amine scrubbing unit, with Cansolv technology, captures 90% of the CO_2 in the flue gas at a purity of 99%. It was modeled as a black box in Aspen, but a detailed flowchart from [13] is included in Appendix 28.8. The power requirement of 9.7 MW accounts for both the steam for regeneration of the solvent and fan blower power for the column. Consistent with correlations in [13], shown in Appendix 28.8, the unit requires 9.7 MW of power and a bare module cost of $266,800,000.

18.1.8. CO_2 Compressor

The CO_2 compressor is a four-stage, intercooled and aftercooled carbon steel centrifugal compressor, with equal compression ratios of 2.98 per stage. It compresses the CO_2 that exits the amine scrubbing unit from 10 psig to 1726 psig, at a polytropic efficiency of 85% with 5 psi pressure drop in the intercoolers. The power required is 12.7 MW and is driven by the steam turbine. Using the guidelines in Chapter 16 of Seider et al. [19] shown in Appendix 28.1, the equipment purchase cost is $5,350,000.

18.1.9. CO_2 Pipeline Cooler

The CO_2 pipeline cooler cools the compressed CO_2 stream exiting the compressor aftercooler from 100 ^oF to 80 ^oF, according to the specs set for the NGCC and Allam cycle CO_2

pipelines. Chilled water at 40 °F provides the required refrigeration, according to Table 17.1 in Seider et al. The area was estimated to be 953 ft^2. All coolers are modeled as black-box shell and tube heat exchangers, with exchanger area and costing information shown in Appendix 28.9. Using the guidelines in Chapter 16 of Seider et al. [19], the purchase cost is $31,900.

18.2. Allam Cycle and ASU Equipment List and Unit Descriptions

18.2.10. Main Air Compressor (MAC)

For this process, due to flow restrictions, the MAC is designed as four compressors in parallel where each compressor is a three-stage, intercooled carbon steel centrifugal compressor. It compresses ambient air from 0 psig to 82 psig at a polytropic efficiency of 85%. The compression ratio per stage is 1.96 and there is a pressure drop of 2 psi in the intercoolers. Each intercooler rejects 16.4 MMBtu/hr of heat to the Allam cycle and 42.7 MMBtu/hr to cooling water. The MAC is driven by the gas turbine and each compressor requires 18.6 MW of power. Using the guidelines in Chapter 16 of Seider et al. [19] shown in Appendix 28.1, the equipment purchase cost for each compressor is $7,370,000.

18.2.11. Booster Air Compressor (BAC)

The BAC is modelled as two compressors in parallel. Each compressor is a four-stage, intercooled carbon steel centrifugal compressor. It compresses a fraction of the compressed air from the MAC at 82 psig to 1035 psig in order to provide the energy needed to boil high pressure liquid oxygen in the cryogenic heat exchanger. It operates at a polytropic efficiency of 85%. The compression ratio per stage is 1.84 and there is a pressure drop of 5 psi in the intercoolers. Each intercooler rejects 24.1 MMBtu/hr of heat to the Allam cycle and 62.9 MMBtu/hr to cooling water. The BAC is driven by the gas turbine and each compressor requires 24.3 MW of power.

Using the guidelines in Chapter 16 of Seider et al. [19] shown in Appendix 28.1, the equipment purchase cost of each BAC is $8,720,000.

18.2.12. Cryogenic Heat Exchanger

The cryogenic heat exchanger cools inlet air from 100 ^oF to cryogenic temperatures and heats the product streams from the LPC to ambient conditions. A warm side delta T was specified by project author, meaning the product streams were specified to leave at 90 ^oF. The total heat exchanged was 281.8 MMBtu/hr, and with a LMTD of 16.3 ^oF, the UA was calculated to be 17.3 MMBtu/hr-F. The cryogenic heat exchanger is a brazed aluminum, plate-fin heat exchanger, and the purchase cost is $4,550,000.

18.2.13. Expander

The expander takes in 10% of the outlet MAC air that exits the cryogenic heat exchanger and expands it from 77 psig to 11 psig for use in the LPC. The expander operates at a polytropic efficiency of 85%. Only one expander is needed for this process and it is designed as a stainless-steel expander that produces 1.5 MW of power. Using the guidelines in Chapter 16 of Seider et al. [19] shown in Appendix 28.11, the equipment purchase cost is $556,000.

18.2.14. High Pressure Column (HPC)

The high pressure column produces a high purity nitrogen stream and slightly enriched oxygen stream that are both fed to the LPC. The height is estimated (from top to bottom) by 3 feet manway + 12 feet of packing + 3 feet space = 18 feet. The diameter of 14 feet was calculated using column internals in RadFrac, assuming structured packing. The column is aluminum. The reflux ratio is 1.1 and the condenser duty is 119 MMBtu/hr. Using the guidelines in Chapter 16 of Seider et al. [19], shown in Appendix in 28.1, the equipment purchase cost is $752,000.

18.2.15. Low Pressure Column (LPC)

The low pressure column produces a high purity nitrogen stream, enriched nitrogen waste stream, and high purity oxygen stream. The height is estimated (from top to bottom) by 2 feet for reboiler feed + 11 feet of packing + 2.5 feet for feed + 9 feet of packing + 2.5 feet for feed + 12 feet packing + 2 feet space = 41 feet. The diameter of 17 feet was calculated using column internals in RadFrac, assuming structured packing. The column is aluminum. The boilup ratio is 2.72 and the reboiler duty is 119 MMBtu/hr. Using the guidelines in Chapter 16 of Seider et al. [19], shown in Appendix in 28.1, the equipment purchase cost is $2,530,000.

18.2.16. O_2-Pump

The O_2 pump pressurizes liquid oxygen from the LPC to Allam cycle conditions for the cryogenic heat exchanger from 13 psig to 1731 psig. Just as in the NGCC, the pump has an efficiency of 85%. It is a centrifugal pump that requires 0.8 MW of power, provided by an electric motor. Using the guidelines in Chapter 16 of Seider et al. [19], shown in Appendices 28.6 and 28.7, the equipment purchase cost for the pump and electric motor are $384,000 and $98,400, respectively.

18.2.17. Natural Gas Compressor (Allam Cycle)

A natural gas compressor is needed to compress the gas to the same pressure as the recycled carbon dioxide and oxygen streams. It receives natural gas at pipeline conditions of 465 psig and compresses the gas to 4336 psig. It was modeled as a two-stage compressor in Aspen, with one intercooler with 5-psi drop. The power requirement is 7.5 MW, and a polytropic efficiency of 85% was assumed. A carbon steel centrifugal compressor, driven by the gas turbine was assumed for this process. Using the guidelines in Chapter 16 of Seider et al. [19], shown in Appendix in 28.1, the equipment purchase cost is $4,160,000.

18.2.18. Combustor and Turbine (Allam Cycle)

The recycled streams and natural gas are both fed to the adiabatic combustor at a constant pressure of 4336 psig, where complete conversion of methane was assumed. The combustion products are then fed into the gas turbine to expand with a ratio of 10 and polytropic efficiency of 85%. The gross output for each of the 4 gas turbines in parallel is 153.6 MW. The combustor and gas turbine units are combined into one piece of equipment and used to drive the centrifugal compressors in the Allam cycle and ASU on the same shaft. For this process, it is designed as four F-class GE gas turbines in parallel, with costing correlation shown in Appendix 28.2. The equipment purchase cost for each turbine is $29,600,000.

18.2.19. Recuperator

The recuperator heats the recycled streams to 1270^{o}F and cools the turbine exhaust to 188^{o}F. There is 3644 MMBtu/hr of heat exchanged, and at a LMTD of 52.6 ^{o}F, the calculated UA value is 69.2 MMBtu/hr-F. The recuperator is a printed circuit heat exchanger (PCHE) and has a purchase cost of $18,200,000, shown in Appendix 28.10.

18.2.20. Cooler1 (Allam Cycle)

Cooler1 cools the recuperator outlet stream further to ambient conditions. Cooling water is assumed to enter at 90 ^{o}F and exit at 120 ^{o}F. The LMTD is 18.7, and the area is 126,094 ft^2. All coolers are treated as black-box shell and tube heat exchangers for the scope of this project. Aspen Capital Cost Estimator (ACCE) was used to verify the cost since it was outside the range specified in [19]. The purchase cost is $1,650,000 and is shown in Appendix 28.9.

18.2.21. Separator

The separator was modelled as a flash vessel in Aspen Plus. There are two flash vessels in parallel due to the large flow rate. The diameter of each vessel is 14 feet, and the height is 43 feet. Diameter calculation based on flooding velocity is shown in Appendix 28.13. The purchase cost of each vessel is $566,000 which was estimated using the cost correlations for vertical pressure vessels in Seider et al. [19].

18.2.22. CO_2 Compressor (Allam Cycle)

The CO_2 compressor is designed as four compressors in parallel. Each compressor is a four-stage, intercooled carbon steel centrifugal compressor. It compresses the CO_2 to pipeline specifications from 232 psig to 1731 psig at a polytropic efficiency of 85%. The compression ratio per stage is 1.61 and there is a pressure drop of 5 psi in the intercoolers. The gas turbine drives the compressors, and each compressor requires 35.6 MW of power. Using the guidelines in Chapter 16 of Seider et al. [19] shown in Appendix 28.1, the equipment purchase cost for each compressor is $11,100,000.

18.2.23. Cooler2 (Allam Cycle)

Cooler2 transfers heat from the purge carbon dioxide stream to the water exiting the flash vessel. The purge stream outlet temperature was specified as 80^{o}F, according to the pipeline specifications. The total heat exchanged is 5.3 MMBtu/hr and the LMTD is 10.4 ^{o}F. Area and cost calculations are shown in Appendix 28.9. The cooler is a black-box shell and tube heat exchanger, as assumed for all coolers. The purchase cost of $65,000 was calculated from correlations in Seider et al. [19] shown in Appendix 28.9.

18.2.24. Cooler3 (Allam Cycle)

Cooler3 cools the carbon dioxide outlet stream further to ambient conditions. Cooling water enters at 90 ^{o}F and exits at 93 ^{o}F. The LMTD is 4 and the area is 67,599 ft^2. All coolers are treated as black-box shell and tube heat exchangers for the scope of this project. Aspen

Capital Cost Estimator (ACCE) was used to verify the cost since it was outside the range specified in [19]. The purchase cost is $1,200,000 and is shown in Appendix 28.9.

18.2.25. Recycle CO_2-Pump

The recycle carbon dioxide pumps the supercritical fluid to the combustion temperature. The pump has an efficiency of 85%. Two pumps run in parallel, each with 11.1 MW required and a pressure head of 8,961 feet. The pump is driven by one of the four gas turbines. The purchase cost of $1,540,000 was estimated with ACCE and is shown in Appendix 28.15.

18.2.26. O_2 and Recycle CO_2-Pump

The oxygen and recycle carbon dioxide pump the supercritical fluid to the combustion temperature. The pump has an efficiency of 85%. Two pumps run in parallel, each with 10.0 MW required and a pressure head of 10,400 feet. The pump is driven by one of the four gas turbines and is a diffuser style barrel pump. Examples of barrel pumps provided by Goulds and Sulzer are shown in Appendix 28.15. The purchase cost of $1,950,000 was estimated with ACCE and is shown in Appendix 28.15.

18.2.27. ASU/Allam HX

The ASU/Allam-HX provides heat integration from the MAC and BAC inter and aftercoolers to the recycled carbon dioxide and oxygen streams in the Allam cycle. The recycle streams are heated to 170 ^{o}F, and the total heat exchanged is 114 MMBtu/hr. Area and cost calculations are shown in Appendix 28.9. The cooler is a black-box shell and tube heat exchanger, as assumed for all coolers, and the purchase cost of $580,000 is from the correlations in Seider et al. [19].

18.3. Equipment List and Unit Descriptions not shown in PFD

18.3.28. Coldbox

The coldox is a rectangular box that insulates the HPC and LPC. It was costed as a vertical pressure vessel, and the purchase cost of $349,000 is shown in Appendix 28.13.

18.3.29. Reboiler/Condenser

The reboiler of the LPC and condenser of the HPC have equal duties by design. The duty is 119 MMBtu/hr and heat exchanges between liquid oxygen in the LPC bottoms and high purity nitrogen in the HPC distillate. The reboiler and condenser were modelled as a heat exchanger with the same cost correlation as the cryogenic heat exchanger. The purchase cost of $1,250,000 is shown in Appendix 28.10.

18.3.30. Natural Gas Pipeline

The pipeline is 10 miles long and supplies natural gas at 100 ^oF.and 450 psig, as specified in [12]. The bare module cost of $12,300,000 is shown in Appendix 28.15.

18.3.31. CO_2 Pipeline

The pipeline is 10 miles long and delivers carbon dioxide at 80 ^oF.and 1726 psig, as specified in Section 14. The bare module cost of $3,070,000 is also calculate from [21] and shown in Appendix 28.15.

18.3.32. Accessory Electric Plant

From NETL, the accessory electric plant, "includes generator equipment, station service equipment, conduit and cable tray, wire, protective equipment, power transformers, and foundations" [12]. The bare module cost of $18,000,000 is included in Appendix 28.15.

Specification Sheets

19.1. NGCC Equipment Specification Sheets

19.1.1. Natural Gas Compressor (NGCC)

Natural Gas Compressor (NGCC)			
	Item		Compressor
	Item No.		1
	No. Required		1
Function:	Compresses natural gas feed to combustor pressure		
Operation:	Continuous		
Streams:		103	104
Inlet/Outlet:		In	Out
Temperature (^oF)		100	141
Pressure (psig)		450	585
Mass Flow (tons/hr)		63	63
Molar Flow (lbmol/hr)		7846	7846
Molar Composition			
Oxygen		0	0
Nitrogen		0	0
Methane		1	1
Water		0	0
Carbon Dioxide		0	0
Volumetric Flow (cuft/min)		1591	1326
Design Data:			
Net Work (MW):		0.75	
Net Heat Duty (MMBtu/hr):		0	
Compression Ratio:		1.29	
1-stage, reciprocating compressor			
carbon steel, driven by gas turbine			
Utilities:	none		
Comments:	polytropic efficiency of 85%		
	costs included in Appendix 28.1		

19.1.2a. Air Compressor (NGCC)

Air Compressor (NGCC)

	Item		Compressor
	Item No.		2a
	No. Required		2
Function:	Compresses inlet air for combustion		
Operation:	Continuous		
Streams:		101	102
Inlet/Outlet:		In	Out
Temperature (^oF)		70	1173
Pressure (psig)		0	585
Mass Flow (tons/hr)		1609	1609
Molar Flow (lbmol/hr)		111492	111492
Molar Composition			
Oxygen		0.21	0.21
Nitrogen		0.79	0.79
Methane		0.00	0.00
Water		0.00	0.00
Carbon Dioxide		0.00	0.00
Volumetric Flow (cuft/min)		718293	54910
Design Data (per compressor, 2 in parallel):			
Net Work (MW):		264.7	
Net Heat Duty (MMBtu/hr):		0	
Compression Ratio		40.8	
single stage, centrifugal compressor; 2 in parallel			
Utilities:	none		
Comments:	isentropic efficiency of 85%		
	combined with combustor and gas turbine in GE F-Class Turbine		
	costs included in Appendix 28.2		

19.1.2b. Combustor (NGCC)

Combustor (NGCC)

	Item			Combustor
	Item No.			2b
	No. Required			2
Function:	Combusts natural gas with oxygen from air			
Operation:	Continuous			
Streams:		102	104	105
Inlet/Outlet:		In	In	Out
Temperature (^oF)		1173	141	2491
Pressure (psig)		585	585	585
Mass Flow (tons/hr)		1609	32	1640
Molar Flow (lbmol/hr)		111492	3923	115415
Molar Composition				
Oxygen		0.21	0.00	0.13
Nitrogen		0.79	0.00	0.76
Methane		0.00	1.00	0.00
Water		0.00	0.00	0.07
Carbon Dioxide		0.00	0.00	0.03
Volumetric Flow (cuft/min)		54910	663	102224
Design Data:				
Net Work (MW):			0	
Net Heat Duty (MMBtu/hr):			0	
Utilities:	none			
Comments:	adiabatic combustor			
	2 in parallel			
	combined with compressor and gas turbine in GE F-Class Turbine			
	costs included in Appendix 28.2			

19.1.2c. Gas Turbine (NGCC)

Gas Turbine (NGCC)

	Item		Turbine
	Item No.		2c
	No. Required		2
Function:	Expands combustor outlet stream to produce work		
Operation:	Continuous		
Streams:		105	106
Inlet/Outlet:		In	Out
Temperature (^oF)		2491	1174
Pressure (psig)		585	10
Mass Flow (tons/hr)		1640	1640
Molar Flow (lbmol/hr)		115415	115415
Molar Composition			
Oxygen		0.13	0.13
Nitrogen		0.76	0.76
Methane		0.00	0.00
Water		0.07	0.07
Carbon Dioxide		0.03	0.03
Volumetric Flow (cuft/min)		102224	1365868
Design Data (per turbine, 2 in parallel):			
Net Work (MW):		-381.0	
Net Heat Duty (MMBtu/hr):		0	
Expansion Ratio:		24	
Utilities:	none		
Comments:	2 GE F-Class turbines in parallel		
	isentropic efficieny of 85%		
	costs included in Appendix 28.2		

19.1.3. Heat Recovery Steam Generator (HRSG)

Heat Recovery Steam Generator (HRSG)					
	Item				Heat Exchanger
	Item No.				3
	No. Required				1
Function:	Exhchanges heat from turbine exhaust to generate steam				
Operation:	Continuous				
Streams:		106	111	107	108
Inlet/Outlet:		In	In	Out	Out
Temperature (^oF)		1174	100	400	854
Pressure (psig)		10	400	10	400
Mass Flow (tons/hr)		3280	483	3280	483
Molar Flow (lbmol/hr)		230830	53610	230830	53610
Molar Composition					
Oxygen		0.13	0.00	0.13	0.00
Nitrogen		0.76	0.00	0.76	0.00
Methane		0.00	0.00	0.00	0.00
Water		0.07	1.00	0.07	1.00
Carbon Dioxide		0.03	0.00	0.03	0.00
Volumetric Flow (cuft/min)		2731736	263	1437342	29375
Design Data:					
Net Work (MW):				0	
Heat Exchanged (MMBtu/hr):				1370	
Net Heat Duty (MMBtu/hr):				0	
shell and tube heat exchanger, carbon steel					
tube: 0.75in OD; 186in length; 1 pass					
6068 tubes and 12 baffles					
Utilities:	boiler-feed water				
Comments:	detailed HX design included in Appendix 28.4				
	costs included in Appendix 28.3				

19.1.4. Steam Turbine

Steam Turbine

	Item		Turbine
	Item No.		4
	No. Required		1
Function:	Produces work by expanding high-pressure steam		
Operation:	Continuous		
Streams:		108	109
Inlet/Outlet:		In	Out
Temperature (^oF)		854	182
Pressure (psig)		400	-8
Mass Flow (tons/hr)		483	483
Molar Flow (lbmol/hr)		53610	53610
Molar Composition			
Oxygen		0.00	0.00
Nitrogen		0.00	0.00
Methane		0.00	0.00
Water		1.00	1.00
Carbon Dioxide		0.00	0.00
Volumetric Flow (cuft/min)		29375	835317
Design Data:			
Net Work (MW):		-91.0	
Net Heat Duty (MMBtu/hr):		0	
Utilities:	none		
Comments:	costing and design from (NETL, 2015)		
	drives CO2 Compressor in case 2		
	costs included in Appendix 28.5		

19.1.5. Condenser

Condenser			
	Item	Heat Exchanger	
	Item No.	5	
	No. Required	1	
Function:	Condenses the expanded water vapor		
Operation:	Continuous		
Streams:		109	110
Inlet/Outlet:		In	Out
Temperature (^oF)		182	100
Pressure (psig)		-8	-8
Mass Flow (tons/hr)		483	483
Molar Flow (lbmol/hr)		53610	53610
Molar Composition			
Oxygen		0.00	0.00
Nitrogen		0.00	0.00
Methane		0.00	0.00
Water		1.00	1.00
Carbon Dioxide		0.00	0.00
Volumetric Flow (cuft/min)		835317	263
Design Data:			
Net Work (MW):		0	
Net Heat Duty, from cooling water (MMBtu/hr):		-1061	
shell and tube heat exchanger, carbon steel			
tube: 0.75in OD; 240in length; 4 passes			
8006 tubes and 6 baffles			
Utilities:	cooling water		
Comments:	detailed HX design included in Appendix 28.4		
	costs included in Appendix 28.3		

19.1.6. Pump

Pump (NGCC)

	Item		Pump
	Item No.		6
	No. Required		1
Function:	Pressurizes water stream		
Operation:	Continuous		
Streams:		110	111
Inlet/Outlet:		In	Out
Temperature (°F)		100	100
Pressure (psig)		-8	400
Mass Flow (tons/hr)		483	483
Molar Flow (lbmol/hr)		53610	53610
Molar Composition			
Oxygen		0.00	0.00
Nitrogen		0.00	0.00
Methane		0.00	0.00
Water		1.00	1.00
Carbon Dioxide		0.00	0.00
Volumetric Flow (cuft/min)		263	263
Design Data:			
Net Work (MW):		0.41	
Net Heat Duty (MMBtu/hr):		0	
Pressure Head (ft)		958	
centrifugal pump driven by electric motor			
Utilities:	none		
Comments:	efficiency of 85%		
	costs for pump and motor included in Appendix 28.6 and 28.7		

19.1.7. Cansolv Amine Scrubbing Unit

Amine Scrubbing Unit				
	Item			Separation Unit
	Item No.			7
	No. Required			1
Function:	Separates CO2 from flue gas			
Operation:	Continuous			
Streams:		107	112	113
Inlet/Outlet:		In	Out	Out
Temperature (^oF)		400	86	86
Pressure (psig)		10	10	10
Mass Flow (tons/hr)		3280	3123	157
Molar Flow (lbmol/hr)		230830	223689	7141
Molar Composition				
Oxygen		0.13	0.14	0.00
Nitrogen		0.76	0.79	0.01
Methane		0.00	0.00	0.00
Water		0.07	0.07	0.00
Carbon Dioxide		0.03	0.00	0.99
Volumetric Flow (cuft/min)		1437342	838741	27973
Design Data:				
Net Work (MW):			9.7	
Heat Balance (MMBtu/hr)			33.1	
Cooling Requirement (MMBtu/hr)			-740	
Utilities:	cooling water and steam			
Comments:	amine scrubbing unit is a be black box with economic and performance costs taken from (NETL, 2019)			
	cooling water requirement is included in the capital investment			
	work requirement is for heat of regeneration for solvent			
	operating cost of steam are accounted for in work requirement			
	costs included in Appendix 28.8			

19.1.8. CO_2 Compressor (NGCC with CDR)

CO2 Compressor

	Item		Compressor
	Item No.		8
	No. Required		1
Function:	Increases pressure of CO2 stream		
Operation:	Continuous		
Streams:		113	114
Inlet/Outlet:		In	Out
Temperature (^oF)		86	100
Pressure (psig)		10	1731
Mass Flow (tons/hr)		157	157
Molar Flow (lbmol/hr)		7141	7141
Molar Composition			
Oxygen		0.00	0.00
Nitrogen		0.01	0.01
Methane		0.00	0.00
Water		0.00	0.00
Carbon Dioxide		0.99	0.99
Volumetric Flow (cuft/min)		27973	125
Design Data:			
Net Work (MW):		12.6	
Intercooler Heat Duty (MMBtu/hr):		-71.2	
Compression Ratio (per stage):		2.98	
4-stage, centrifugal compressor with intercoolers			
5-psi drop in intercoolers			
carbon steel, driven by steam turbine			
Utilities:	cooling water		
Comments:	polytropic efficiency of 85%		
	costs included in Appendix 28.1		

19.1.9. Pipeline CO_2 Cooler

Pipeline CO2 Cooler

	Item		Cooler
	Item No.		9
	No. Required		1
Function:	Cools CO2 to pipeline conditions		
Operation:	Continuous		
Streams:		114	115
Inlet/Outlet:		In	Out
Temperature (^oF)		100	80
Pressure (psig)		1731	1726
Mass Flow (tons/hr)		157	157
Molar Flow (lbmol/hr)		7141	7141
Molar Composition			
Oxygen		0.00	0.00
Nitrogen		0.01	0.01
Methane		0.00	0.00
Water		0.00	0.00
Carbon Dioxide		0.99	0.99
Volumetric Flow (cuft/min)		125	129
Design Data:			
Net Work (MW):		0	
Net Heat Duty (MMBtu/hr):		-4.97	
Utilities:	chilled water (40F)		
Comments:	coolers modeled as black-box, shell and tube HX		
	chilled water at 40F is used to cool pipeline CO2 from 100 to 80F		
	costs shown in Appendix 28.9		

19.2. Allam Cycle Equipment Specification Sheets

19.2.10. Main Air Compressor (MAC)

Main Air Compressor (MAC)			
	Item		Compressor
	Item No.		10
	No. Required		4
Function:	Increases pressure of air from ambient conditions		
Operation:	Continuous		
Streams:		201	202
Inlet/Outlet:		In	Out
Temperature (^oF)		70	100
Pressure (psig)		0	82
Mass Flow (tons/hr)		319	319
Molar Flow (lbmol/hr)		22101	22101
Molar Composition			
Nitrogen		0.79	0.79
Oxygen		0.21	0.21
Volumetric Flow (cuft/min)		142388	22748
Design Data (per compressor, 4 in parallel):			
Net Work (MW):		18.6	
Heat to Allam Cycle (MMBtu/hr):		-16.4	
Cooling Water Requirement (MMBtu/hr)		-42.7	
Net Cooling Duty (MMBtu/hr)		-59.1	
Compresion Ratio (per stage)		1.96	
3-stage, centrifugal compressor; 4 in parallel			
intercooled with cooling water; 2-psi drop in intercoolers			
carbon steel, driven by gas turbine			
Utilities:	cooling water		
Comments:	polytropic efficiency of 85%		
	costs for cw intercoolers part of compressor cost		
	costs included in Appendix 28.1		

19.2.11. Booster Air Compressor (BAC)

Booster Air Compresser (BAC)			
	Item		Compressor
	Item No.		11
	No. Required		2
Function:	Boosts air pressure to boil high pressure liquid oxygen		
Operation:	Continuous		
Streams:		205	206
Inlet/Outlet:		In	Out
Temperature (^oF)		100	100
Pressure (psig)		82	1035
Mass Flow (tons/hr)		338	338
Molar Flow (lbmol/hr)		23427	23427
Molar Composition			
Nitrogen		0.79	0.79
Oxygen		0.21	0.21
Volumetric Flow (cuft/min)		24113	2201
Design Data (per compressor, 2 in parallel):			
Net Work (MW):		24.3	
Heat to Allam Cycle (MMBtu/hr):		-24.1	
Cooling Water Requirement (MMBtu/hr)		-62.9	
Net Cooling Duty (MMBtu/hr)		-87.0	
Compression Ratio (per stage)		1.84	
4-stage, centrifugal compressor; 2 in parallel			
intercooled with cooling water; 5-psi drop in compressors			
carbon steel, driven by gas turbine			
Utilities:	cooling water		
Comments:	polytropic efficiency of 85%		
	costs included in Appendix 28.2		

19.2.12. Cryogenic Heat Exchanger

Cryogenic HX

	Item											Heat Exchanger
	Item No.											12
	No. Required											1
Function:	Cools air to cryoginc temps; boils ASU products											
Operation:	Continuous											
Streams:	203	204	206	213	214	216	207	209	210	217	218	219
Inlet/Outlet:	In	In	In	In	In	In	Out	Out	Out	Out	Out	Out
Temperature (^oF)	100	100	100	-313	-306	-278	-150	-234	-234	90	90	90
Pressure (psig)	82	82	1035	8	10	1731	77	77	1035	8	10	1726
Mass Flow (tons/hr)	128	472	676	810	217	248	128	472	676	810	217	248
Molar Flow (lbmol/hr)	8840	32710	46854	57729	15146	15530	8840	32710	46854	57729	15146	15530
Molar Composition												
Nitrogen	0.79	0.79	0.79	0.99	0.83	0.005	0.79	0.79	0.79	0.99	0.83	0.005
Oxygen	0.21	0.21	0.21	0.01	0.17	0.995	0.21	0.21	0.21	0.01	0.17	0.995
Volumetric Flow (cuft/min)	9099	33667	4401	62293	16029	123	5161	13214	648	246663	60545	821

Design Data:	
Net Work (MW):	0
Heat Exchanged (MMBtu/hr):	281.8
LMTD	16.3
UA (MMBtu/hr-F)	17.3
Net Heat Duty (MMBtu/hr):	0
brazed aluminum, plate-fin heat exchanger	

Utilities:	none
Comments:	costing with UA correlation provided by project author
	modelled with MHEATX in Aspen Plus
	heat curve included in Appendix 28.10
	costs included in Appendix 28.10

19.2.13. Expander

Expander

	Item		Expander
	Item No.		13
	No. Required		1
Function:	Recovers work from compressed air fed to LPC		
Operation:	Continuous		
Streams:		207	208
Inlet/Outlet:		In	Out
Temperature (^oF)		-150	-236
Pressure (psig)		77	11
Mass Flow (tons/hr)		128	128
Molar Flow (lbmol/hr)		8840	8840
Molar Composition			
Nitrogen		0.79	0.79
Oxygen		0.21	0.21
Volumetric Flow (cuft/min)		5161	13763
Design Data:			
Net Work (MW):		-1.5	
Net Heat Duty (MMBtu/hr):		0	
stainless steel			
Utilities:	none		
Comments:	polytropic efficiency of 85%		
	costs included in Appendix 28.11		

19.2.14. High Pressure Column (HPC)

High Pressure Column (HPC)

	Item				Packed Column
	Item No.				14
	No. Required				1
Function:	Produces high purity N2 and enriched O2 streams that are fed to LPC				
Operation:	Continuous				
Streams:		209	210	211	212
Inlet/Outlet:		In	In	Out	Out
Temperature (^oF)		-234	-234	-288	-281
Pressure (psig)		77	1035	65	70
Mass Flow (tons/hr)		472	676	382	766
Molar Flow (lbmol/hr)		32710	46854	27224	52340
Molar Composition					
Nitrogen		0.79	0.79	0.99	0.69
Oxygen		0.21	0.21	0.01	0.31
Volumetric Flow (cuft/min)		13214	648	284	510
Design Data:					
Net Work (MW):				0	
Net Heat Duty (MMBtu/hr):				-119	
Relux Ratio (mole)				1.1	
Boilup Ratio (mole)				1.046	
aluminum column with structured packing (10in/stage)					
13 theoretical trays with 10in packing/stage					
diameter = 14ft; height = 18ft					
feed streams 209 and 210 at bottom of column					
Utilities:	none				
Comments:	designed with RadFrac in Aspen Plus, details included in Appendix 28.13				
	costs included in Appendix 28.13				

19.2.15. Low Pressure Column (LPC)

Low Pressure Column (LPC)

	Item	Packed Column
	Item No.	15
	No. Required	1

Function: Produces high purity N2, high purity O2, and waste streams

Operation: Continuous

Streams:	208	211	212	213	214	215
Inlet/Outlet:	In	In	In	Out	Out	Out
Temperature (^oF)	-236	-288	-281	-313	-306	-286
Pressure (psig)	11	65	70	8	10	13
Mass Flow (tons/hr)	128	382	766	810	217	248
Molar Flow (lbmol/hr)	8840	27224	52340	57729	15146	15530
Molar Composition						
Nitrogen	0.79	0.99	0.69	0.99	0.83	0.005
Oxygen	0.21	0.01	0.31	0.01	0.17	0.995
Volumetric Flow (cuft/min)	13763	284	510	62293	16029	120

Design Data:

Net Work (MW):	0
Net Heat Duty (MMBtu/hr):	119
Relux Ratio (mole)	0.397
Boilup Ratio (mole)	2.715

aluminum column with structured packing (10in/stage)
38 theoretical trays with 10in packing/stage
diameter = 17 ft; height = 41ft
208 on stage 15; 211 on stage 1; 212 on stage 25
side stream draw off on stage 13

Utilities: none

Comments: designed with RadFrac in Aspen Plus, details included in Appendix 28.14
costs included in Appendix 28.14

19.2.16. O_2-Pump

O2 Pump

	Item		Pump
	Item No.		16
	No. Required		1
Function:	Increases pressure of LOX to Allam cycle conditions		
Operation:	Continuous		
Streams:		215	216
Inlet/Outlet:		In	Out
Temperature (^{o}F)		-286	-278
Pressure (psig)		13	1731
Mass Flow (tons/hr)		248	248
Molar Flow (lbmol/hr)		15530	15530
Molar Composition			
Nitrogen		0.005	0.005
Oxygen		0.995	0.995
Volumetric Flow (cuft/min)		120	123
Design Data:			
Net Work (MW):		0.8	
Net Heat Duty (MMBtu/hr):		0	
Pressure Head (ft)		3581	
centrifugal pump, driven by electric motor			
Utilities:	none		
Comments:	85% efficiency		
	pump and motor costs included in Appendix 28.6 and 28.8		

19.2.17. Natural Gas Compressor (Allam Cycle)

Natural Gas Compressor (Allam Cycle)

	Item		Compresso
	Item No.		17
	No. Required		1
Function:	Compresses natural gas feed to combustor pressure		
Operation:	Continuous		
Streams:		301	302
Inlet/Outlet:		In	Out
Temperature (^oF)		100	293
Pressure (psig)		450	4336
Mass Flow (tons/hr)		62	62
Molar Flow (lbmol/hr)		7726	7726
Molar Composition			
Oxygen		0	0
Nitrogen		0	0
Methane		1	1
Water		0	0
Carbon Dioxide		0	0
Volumetric Flow (cuft/min)		1591	255
Design Data:			
Net Work (MW):		7.5	
Intercooler Heat Duty (MMBtu/hr):		-15.7	
Compression Ratio (per stage):		3.0	
2-stage centrifugal compressor, with equal compression ratios			
carbon steel, driven by gas turbine			
Utilities:	cooling water		
Comments:	polytropic efficiency of 85%		
	costs included in Appendix 28.1		

19.2.18a. Combustor (Allam Cycle)

Combustor (Allam Cycle)

	Item				Combustor
	Item No.				18a
	No. Required				4
Function:	Combusts oxygen and natural gas				
Operation:	Continuous				
Streams:		302	319	325	303
Inlet/Outlet:		In	In	In	Out
Temperature (^oF)		293	1270	1270	2062
Pressure (psig)		4336	4336	4336	4336
Mass Flow (tons/hr)		15	699	541	1256
Molar Flow (lbmol/hr)		1932	31896	25755	59582
Molar Composition					
Oxygen		0	0.00	0.15	0.00
Nitrogen		0	0.01	0.01	0.01
Methane		1	0.00	0.00	0.00
Water		0	0.00	0.00	0.07
Carbon Dioxide		0	0.99	0.84	0.92
Volumetric Flow (cuft/min)		398	2483	2002	6634
Design Data (per combustor, 4 in parallel)					
Net Work (MW):				0	
Net Heat Duty (MMBtu/hr):				0	
Utilities:	none				
Comments:	adiabatic combustor				
	4 in parallel				
	combined with gas turbine and priced similar to GE F-Class Turbine in NGC				
	costs included in Appendix 28.2				

19.2.18b. Gas Turbine (Allam Cycle)

Gas Turbine (Allam Cycle)

	Item		Turbine
	Item No.		18b
	No. Required		4
Function:	Expands combustor outlet stream to produce work		
Operation:	Continuous		
Streams:		303	304
Inlet/Outlet:		In	Out
Temperature (^oF)		2062	1421
Pressure (psig)		4336	420
Mass Flow (tons/hr)		1256	1256
Molar Flow (lbmol/hr)		59582	59582
Molar Composition			
Oxygen		0.00	0.00
Nitrogen		0.01	0.01
Methane		0.00	0.00
Water		0.07	0.07
Carbon Dioxide		0.92	0.92
Volumetric Flow (cuft/min)		6634	46461
Design Data (per turbine, 4 in parallel)			
Net Work (MW):		-153.6	
Net Heat Duty (MMBtu/hr):		0	
Expansion Ratio:		10.0	
Utilities:	none		
Comments:	combined with combustor and priced similar to GE F-Class Turbine in NGC		
	polytropic efficieny of 85%		
	4 in parallel		
	costs included in Appendix 28.4		

19.2.19. Recuperator

Recuperator

Item	Heat Exchanger
Item No.	19
No. Required	1

Function: Heats recycle streams and cools turbine exhaust

Operation: Continuous

Streams:	304	318	324	305	319	325
Inlet/Outlet:	In	In	In	Out	Out	Out
Temperature (^oF)	1421	170	170	188	1270	1270
Pressure (psig)	420	4341	4341	415	4336	4336
Mass Flow (tons/hr)	5022	2795	2165	5022	2795	2165
Molar Flow (lbmol/hr)	238329	127584	103019	238329	127584	103019
Molar Composition						
Oxygen	0.00	0.00	0.15	0.00	0.00	0.15
Nitrogen	0.01	0.01	0.01	0.01	0.01	0.01
Methane	0.00	0.00	0.00	0.00	0.00	0.00
Water	0.07	0.00	0.00	0.07	0.00	0.00
Carbon Dioxide	0.92	0.99	0.84	0.92	0.99	0.84
Volumetric Flow (cuft/min)	185845	2093	1927	56495	9930	8007

Design Data:

Net Work (MW):	0
Total Heat Exchanged (MMBtu/hr)	3644
LMTD (F)	52.6
UA (MMBtu/hr-F)	69.2
Net Heat Duty (MMBtu/hr):	0

printed circuit heat exchanger

Utilities: none

Comments: recuperator modelled as MHEATX in Aspen Plus
minimum delta T approach of 3.6F
heat curve included in Appendix 28.10
costs included in Appendix 28.10

19.2.20. Cooler1 (Allam Cycle)

Cooler1 (Allam Cycle)

	Item		Cooler
	Item No.		20
	No. Required		1
Function:	Cools recuperator outlet to ambient temperature		
Operation:	Continuous		
Streams:		305	306
Inlet/Outlet:		In	Out
Temperature (^oF)		188	92
Pressure (psig)		415	415
Mass Flow (tons/hr)		5022	5022
Molar Flow (lbmol/hr)		238329	238329
Molar Composition			
Oxygen		0.00	0.00
Nitrogen		0.01	0.01
Methane		0.00	0.00
Water		0.07	0.07
Carbon Dioxide		0.92	0.92
Volumetric Flow (cuft/min)		56495	43798
Design Data:			
Net Work (MW):		0	
Net Heat Duty (MMBtu/hr):		-354.2	
LMTD (F)		18.7	
Area (sqft)		126,094	
Utilities:	cooling water		
Comments:	coolers modeled as black-box, shell and tube HX		
	costs and area calculation included in Appendix 28.9		

19.2.21. Separator

Separator

	Item	Pressure Vessel		
	Item No.	21		
	No. Required	2		
Function:	Separates CO2 and water in flash vessel			
Operation:	Continuous			
Streams:		307	308	310
Inlet/Outlet:		In	Out	Out
Temperature (^oF)		71	71	71
Pressure (psig)		232	232	232
Mass Flow (tons/hr)		2511	70	2441
Molar Flow (lbmol/hr)		119165	7728	111437
Molar Composition				
Oxygen		0.00	0	0.00
Nitrogen		0.01	0	0.01
Methane		0.00	0	0.00
Water		0.07	0.999	0.00
Carbon Dioxide		0.92	0.001	0.99
Volumetric Flow (cuft/min)		39049	39	39010
Design Data (per separator, 2 in parallel)				
Net Work (MW):			0	
Net Heat Duty (MMBtu/hr):			0	
Diameter = 14.3				
Height = 43				
Utilities:	none			
Comments:	flash drum sizing included in Appendix 28.13			
	costs included in Appendix 28.13			

19.2.22. CO_2 Compressor (Allam Cycle)

CO2 Compressor (Allam Cycle)			
	Item		Compressor
	Item No.		22
	No. Required		4
Function:	Increases pressure of CO2 stream to pipeline spec		
Operation:	Continuous		
Streams:		310	311
Inlet/Outlet:		In	Out
Temperature (^oF)		71	100
Pressure (psig)		232	1731
Mass Flow (tons/hr)		1221	1221
Molar Flow (lbmol/hr)		55719	55719
Molar Composition			
Oxygen		0.00	0.00
Nitrogen		0.01	0.01
Methane		0.00	0.00
Water		0.00	0.00
Carbon Dioxide		0.99	0.99
Volumetric Flow (cuft/min)		19505	1014
Design Data (per compressor, 4 in parallel):			
Net Work (MW):		35.6	
Cooling Water Duty (MMBtu/hr):		317.5	
Compression Ratio (per stage):		1.61	
4-stage centrifugal compressor, with equal compression ratios; 4 in parallel			
5-psi drop in intercoolers			
carbon steel, driven by gas turbine			
Utilities:	cooling water		
Comments:	polytropic efficincy of 85%		
	costs included in Appendix 28.2		

19.2.23. Cooler2 (Allam Cycle)

Cooler2

	Item				Heat Exchanger
	Item No.				23
	No. Required				1
Function:	Cools purge CO2 to pipeline spec using H2O from flash vessel				
Operation:	Continuous				
Streams:		308	312	309	313
Inlet/Outlet:		In	In	Out	Out
Temperature (^oF)		71	100	88	80
Pressure (psig)		232	1731	232	1726
Mass Flow (tons/hr)		139	171	139	171
Molar Flow (lbmol/hr)		15455	7801	15455	7801
Molar Composition					
Oxygen		0.00	0.00	0.00	0.00
Nitrogen		0.00	0.01	0.00	0.01
Methane		0.00	0.00	0.00	0.00
Water		0.999	0.00	0.999	0.00
Carbon Dioxide		0.001	0.99	0.001	0.99
Volumetric Flow (cuft/min)		77	142	78	122
Design Data:					
Net Work (MW):				0	
Heat Exchanged (MMBtu/hr):				5.3	
LMTD				10.4	
Area (sqft)				3,422	
Utilities:	none				
Comments:	coolers modeled as black-box, shell and tube HX costs and area calculation included in Appendix 28.9				

19.2.24. Cooler3 (Allam Cycle)

Cooler3

	Item		Cooler
	Item No.		24
	No. Required		1
Function:	Cools recycled CO2 stream for pump inlet		
Operation:	Continuous		
Streams:		314	315
Inlet/Outlet:		In	Out
Temperature (^oF)		100	95
Pressure (psig)		1731	1731
Mass Flow (tons/hr)		4711	4711
Molar Flow (lbmol/hr)		215073	215073
Molar Composition			
Oxygen		0.00	0.00
Nitrogen		0.01	0.01
Methane		0.00	0.00
Water		0.00	0.00
Carbon Dioxide		0.99	0.99
Volumetric Flow (cuft/min)		3913	3744
Design Data:			
Net Work (MW):		0	
Net Heat Duty (MMBtu/hr):		-39.7	
LMTD (F)		4	
Area (sqft)		67,599	
Utilities:	cooling water		
Comments:	coolers modeled as black-box, shell and tube HX		
	costs and area calculation included in Appendix 28.8		

19.2.25. Recycle CO_2-Pump

Recycle CO2-Pump			
	Item		Pump
	Item No.		25
	No. Required		2
Function:	Pressurizes recycled CO2 stream		
Operation:	Continuous		
Streams:		316	317
Inlet/Outlet:		In	Out
Temperature (^oF)		95	149
Pressure (psig)		1731	4341
Mass Flow (tons/hr)		1398	1398
Molar Flow (lbmol/hr)		63792	63792
Molar Composition			
Oxygen		0.00	0.00
Nitrogen		0.01	0.01
Methane		0.00	0.00
Water		0.00	0.00
Carbon Dioxide		0.99	0.99
Volumetric Flow (cuft/min)		1111	976
Design Data (per pump, 2 in parallel):			
Net Work (MW):		11.1	
Net Heat Duty (MMBtu/hr):		0	
Pressure Head (ft)		8961	
barrel pump			
carbon steel, driven by gas turbine			
Utilities:	none		
Comments:	85% efficiency		
	barrel pump is required to produce pressure head above centrifugal limit		
	2 in parallel to match vendor barrel pump flow rate limitations		
	cost is estimated as a centrifugal pump in ACCE		
	costs included in Appendix 28.15		

19.2.26. O_2 and Recycle CO_2-Pump

O2/Recycle CO2-Pump

	Item		Pump
	Item No.		26
	No. Required		2
Function:	Pressurizes O2 and recycled CO2 stream		
Operation:	Continuous		
Streams:		322	323
Inlet/Outlet:		In	Out
Temperature (^oF)		75	144
Pressure (psig)		1726	4341
Mass Flow (tons/hr)		1083	1083
Molar Flow (lbmol/hr)		51510	51510
Molar Composition			
Oxygen		0.15	0.15
Nitrogen		0.01	0.01
Methane		0.00	0.00
Water		0.00	0.00
Carbon Dioxide		0.84	0.84
Volumetric Flow (cuft/min)		997	843
Design Data (per pump, 2 in parallel):			
Net Work (MW):		10.0	
Net Heat Duty (MMBtu/hr):		0	
Pressure Head (ft)		10,400	
barrel pump			
carbon steel, driven by gas turbine			
Utilities:	none		
Comments:	85% efficiency		
	barrel pump is required to produce pressure head above centrifugal limit		
	2 in parallel to match vendor barrel pump flow rate limitations		
	cost is estimated as a centrifugal pump in ACCE		
	costs included in Appendix 28.15		

19.2.27. ASU/Allam HX

ASU/Allam-HX

	Item				Heat Exchanger
	Item No.				27
	No. Required				1
Function:	Preheats recycle streams to recuperator from ASU intercoolers				
Operation:	Continuous				
Streams:		317	323	318	324
Inlet/Outlet:		In	In	Out	Out
Temperature (^oF)		149	144	170	170
Pressure (psig)		4341	4341	4341	4341
Mass Flow (tons/hr)		2795	2165	2795	2165
Molar Flow (lbmol/hr)		127584	103019	127584	103019
Molar Composition					
Oxygen		0.00	0.15	0.00	0.15
Nitrogen		0.01	0.01	0.01	0.01
Methane		0.00	0.00	0.00	0.00
Water		0.00	0.00	0.00	0.00
Carbon Dioxide		0.99	0.84	0.99	0.84
Volumetric Flow (cuft/min)		1951	1686	2093	1927
Design Data:					
Net Work (MW):				0	
Heat Exchanged (MMBtu/hr):				114	
Net Heat Duty (MMBtu/hr)				0	
LMTD (F)				53.4	
Area (sqft)				14,238	
Utilities:	none				
Comments:	coolers modeled as black-box, shell and tube HX costs and area calculation included in Appendix 28.8				

19.3. Specification Sheets for Equipment not shown in PFD

19.3.28. Coldbox

Coldbox		
	Item	Coldbox
	Item No.	28
	No. Required	1
Function:	Maintains distillation column at cryogenic temperatures	
Operation:	N/A	
Streams:		N/A
Temperature (°F)		-313
Pressure (psig)		0.1
Design Data:		
Net Work (MW):	0	
Net Heat Duty (MMBtu/hr):	0	
width = 19ft		
height = 60ft		
Utilities:	none	
Comments:	rectangular box filled with perlite for insulation of HPC & LPC	
	costs included in Appendix 28.13 for pressure vessel	

19.3.29. Reboiler/Condenser

Reboiler/Condenser

	Item	Heat Exchanger
	Item No.	29
	No. Required	1
Function:	Transfers heat from HPC condenser to LPC reboiler	
Operation:	Continuous	
Streams:		HPC dist. and LPC bottoms
Temperature (^oF)		-313
Pressure (psig)		0.1
Design Data:		
Net Work (MW):		0
Total exchanger duty (MMBtu/hr):		119
Net Heat Duty (MMBtu/hr):		0
Utilities:	none	
Comments:	modelled as HX with same $/UA correlation as cryogenic HX	
	costs included in Appendix 28.10	

19.3.30. Natural Gas Pipeline

Natural Gas Pipeline		
	Item	Pipeline
	Item No.	30
	No. Required	1 (for each plant)
Function:	Provides natural gas feedstock to each powerplant	
Operation:	Continuous	
Streams:		N/A
Inlet/Outlet:		
Temperature (^oF)		100
Pressure (psig)		450
Design Data:		
Net Work (MW):		0
Net Heat Duty (MMBtu/hr):		0
10 mile pipeline		
supplies natural gas at 100F and 450psig		
Utilities:	none	
Comments:	length, specs, and conditions specified by (NETL, 2015)	
	capital investment is assumed to include piepline pressure boosters	
	costs included in Appendix 28.16	

19.3.31. CO_2 Pipeline

CO2 Pipeline

	Item	Pipeline
	Item No.	31
	No. Required	1 (for each plant)
Function:	Connects liquid CO2 to larger pipeline infrastructure	
Operation:	Continuous	
Streams:		N/A
Inlet/Outlet:		
Temperature (^oF)		80
Pressure (psig)		1726
Design Data:		
Net Work (MW):	0	
Net Heat Duty (MMBtu/hr):	0	
10 mile pipeline		
Utilities:	none	
Comments:	delivers CO2 to established CO2 pipeline network	
	length, specs, and conditions specified in 'Assembly of Database'	
	capital investment is assumed to include piepline pressure boosters	
	costs included in Appendix 28.16	

19.3.32. Accessory Electric Plant

Accessory Electric Plant

	Item	Electrical Equipment
	Item No.	32
	No. Required	1 (for each plant)
Function:	Converts mechanical work to electricity that can be transmitted	
Operation:	Continuous	
Streams:		N/A
Inlet/Outlet:		
Temperature (^oF)		70
Pressure (psig)		0
Design Data:		
Net Work (MW):		0
Net Heat Duty (MMBtu/hr):		0
Utilities:	none	
Comments:	treated as black box; costing and design from (NETL, 2015)	
	Includes generator equip, station service equip, coduit and cable tray, wire, protective equip, power transformers, foundations	
	costs included in Appendix 28.16	

Equipment Cost Summary

20.1. NGCC Equipment Costs

The purchase cost for the major equipment in the NGCC and NGCC with CDR is shown in Table 20.1. As detailed in Chapter 16 of Seider et al., bare module factors are used to estimate bare module costs, which includes purchase plus installation costs. The total bare module cost is $264MM for case 1, the NGCC, and $546MM for case 2, the NGCC with CDR. The bare module cost summary is shown in Table 20.1, and equipment IDs are labeled to reference their specifications in Section 19.

Table 20.1: Total Bare Module Cost for NGCC and NGCC with CDR

ID	Equipment Name	No. Purchased	Purchase Cost (USD)	Bare Module Factor	Bare Module Cost (USD)
1	Natural Gas Compressor	1	$ 699,000	2.15	$ 1,500,000
2	Compressor, Combustor, Turbine	2	$ 35,800,000	2	$ 143,000,000
3	HRSG	1	$ 13,700,000	3.17	$ 43,500,000
4	Steam turbine	1	$ 14,600,000	2	$ 29,100,000
5	Condenser	1	$ 5,390,000	3.17	$ 17,100,000
6	Water Pump	1	$ 211,000	3.3	$ 695,000
6	Water Pump Motor	1	$ 65,800	3.21	$ 211,000
30	Natural Gas Pipeline	1	$ 12,300,000	1	$ 12,300,000
32	Accessory Electric Plant	1	$ 18,000,000	1	$ 18,000,000
	TOTAL (case 1)				$ 264,000,000
7	Amine Scrubbing Unit	1	$267,000,000	1	$ 267,000,000
8	CO2 Compressor	1	$ 5,350,000	2.15	$ 11,500,000
9	CO2 Pipeline Cooler	1	$ 31,900	3.17	$ 101,000
31	CO2 Pipeline	1	$ 3,070,000	1	$ 3,070,000
	TOTAL (case 2, with CDR)				**$ 546,000,000**

20.2. Allam Cycle Equipment Costs

There is a total bare module cost of $594MM for case 3, the Allam cycle with an integrated ASU. The total bare module cost for the ASU alone is $136MM. The bare module cost summary is shown in Table 20.2, and equipment IDs are labeled to reference their specifications in Section 19.

Table 20.2: Total Bare Module Cost for the Allam cycle

ID	Equipment Name	No. Purchased	Purchase Cost (USD)	Bare Module Factor	Bare Module Cost (USD)
10	MAC	4	$ 7,370,000	2.15	$ 63,400,000
11	BAC	2	$ 8,720,000	2.15	$ 37,500,000
12	Cryogenic-HX	1	$ 4,550,000	3	$ 13,600,000
13	Expander	1	$ 556,000	3.21	$ 1,790,000
14	HPC Packed	1	$ 752,000	4.16	$ 3,130,000
15	LPC Packed	1	$ 2,530,000	4.16	$ 10,500,000
16	O2-Pump	1	$ 384,000	3.3	$ 1,270,000
16	O2-Pump Motor	1	$ 98,400	3.21	$ 316,000
28	Coldbox	1	$ 349,000	3.21	$ 1,120,000
29	Reboil/Condenser	1	$ 1,250,000	3	$ 3,760,000
17	NG-Compressor	1	$ 4,160,000	2.15	$ 8,940,000
18	Combustor&Turbine	4	$ 29,600,000	2	$ 237,000,000
19	Recuperator	1	$ 18,200,000	3	$ 54,600,000
20	Cooler1	1	$ 1,650,000	2.2	$ 3,630,000
21	Separator	2	$ 566,000	4.16	$ 4,710,000
22	CO2-Compressor	4	$ 11,100,000	2.15	$ 95,400,000
23	Cooler2	1	$ 65,000	3.17	$ 206,000
24	Cooler3	1	$ 1,200,000	3.17	$ 3,790,000
25	ReCO2-Pump	2	$ 1,540,000	2	$ 6,180,000
26	O2/ReCO2-Pump	2	$ 1,950,000	2	$ 7,810,000
27	ASU/Allam HX	1	$ 580,000	3.17	$ 1,840,000
30	Natural Gas Pipeline	1	$ 12,300,000	1	$ 12,300,000
31	CO2 Pipeline	1	$ 3,070,000	1	$ 3,070,000
32	Accessory Electric Plant	1	$ 18,000,000	1	$ 18,000,000
	TOTAL				**$ 594,000,000**

Table 20.3 details the source and Appendix number where costing information was derived. The 'Equipment Design Sheet" refers to the costing spreadsheet created by Professor Russell Dunn at Vanderbilt University, which utilizes the equipment design correlations provided in Chapter 16 of Seider et al. The water pump (B6) in the NGCC and O_2 pump (B16) in the ASU were designed within the range provided in Seider et al., but the larger barrel pumps (B25, B26) were outside of the range and estimated with Aspen Capital Cost Estimator (ACCE). It was advised to use an adjusted bare module factor of two for the larger pumps. The project author, Adam Brostow, specified the correlation used for the cryogenic heat exchanger (B12), recuperator (B19), and condenser/reboiler complex (B29). The natural gas pipeline (B30), CO_2 pipeline (B31), and accessory electric plant (B32) were specified as constant boundary investments for the NGCC with CDR and Allam cycle, and therefore, show the same bare module cost in Table 20.1 and Table 20.2. The costing data found for these three blocks were given as installed costs, so a bare module factor of one is used.

Table 20.3 Sources and Referenced Appendices for Equipment Types

Equipment Type	Source	Appendix
Compressor	Equipment Design Sheet	Appendix 28.1
Gas Turbine	DOE, 2016 & NETL, 2015	Appendix 28.2
HRSG	--	Appendix 28.3
Steam Turbine	NETL, 2015	Appendix 28.4
Condenser	--	Appendix 28.5
Centrifugal Pumps	Equipment Design Sheet	Appendix 28.6
Electric Motor	Equipment Design Sheet	Appendix 28.7
Amine Scrubbing Unit	NETL, 2019	Appendix 28.8
Coolers	Equipment Design Sheet	Appendix 28.9
Allam Cycle HXs	Correlation from Project Author	Appendix 28.10
Expander	Chapter 16 Seider et al	Appendix 28.11
Packed Columns	Equipment Design Sheet	Appendix 28.12
Pressure Vessels	Equipment Design Sheet	Appendix 28.13
Allam Cycle Pumps	ACCE	Appendix 28.14
Pipelines & Electric Plant	NETL and McCollum et al	Appendix 28.15

Total Permanent Investment Summary

21.1. Assumptions for Total Permanent Investment

The total permanent investment was calculated using the bare module costs from Section 20 and guidelines from Chapter 17 of Seider et al. [19]. A modified version of the 'Profitability-Analysis-4.0.xls' included with the online package of Seider et al. was used to calculate the total permanent investment.

Table 21.1 outlines the assumptions made in calculating the total permanent investment. The assumptions were held consistent for all three cases. The plant will operate in the US Gulf Coast, so a site factor of 1.0 is used, according to Seider et al. [19].

Table 21.1: Assumptions for Total Permanent Investment Calculation

Total Bare Module Cost:	Calculated in Section 20
Storage tanks and spares:	None; Pipeline feed and CO2 byproduct
Computers and Software:	None
Catalysts:	Catalyst for Amine unit included in bare module cost
Cost of Site Preparations:	5% of Total Bare Module Cost
Cost of Serive Facilities:	5% of Total Bare Module Cost
Allocated Costs for Utility Plants:	Accounted for in varibale utility costs
Cost of Contingencies and Contractor's Fees:	18% of Direct Permanent Investment
Cost of Land:	2% of Total Depreciable Capital
Cost of Royalties:	None
Cost of Plant Startup:	10% of Total Depreciable Capital

21.2. NGCC Total Permanent Investment

Table 21.2: Total Permanent Investment for NGCC with no CDR

Investment Summary		
Installed Equipment Costs:		
Total:		**$264,400,000**
Direct Permanent Investment		
Cost of Site Preparations:	$ 13,200,000	
Cost of Service Facilities:	$ 13,200,000	
Allocated Costs for utility plants and related facilities:	$ -	
Direct Permanent Investment		**$291,000,000**
Total Depreciable Capital		
Cost of Contingencies & Contractor Fees	$ 52,400,000	
Total Depreciable Capital		**$343,000,000**
Total Permanent Investment		
Cost of Land:	$ 6,860,000	
Cost of Royalties:	$ -	
Cost of Plant Start-Up:	$ 34,300,000	
Total Permanent Investment - Unadjusted		$386,000,000
Site Factor		1.00
Total Permanent Investment		**$384,000,000**

Table 21.3: Total Permanent Investment for NGCC with CDR

Investment Summary

Installed Equipment Costs:		
Total:		**$ 546,000,000**
Direct Permanent Investment		
Cost of Site Preparations:	$ 27,300,000	
Cost of Service Facilities:	$ 27,300,000	
Allocated Costs for utility plants and related facilities:	$ -	
Direct Permanent Investment		**$ 301,000,000**
Total Depreciable Capital		
Cost of Contingencies & Contractor Fees	$ 108,000,000	
Total Depreciable Capital		**$ 709,000,000**
Total Permanent Investment		
Cost of Land:	$ 14,200,000	
Cost of Royalties:		
Cost of Plant Start-Up:	$ 70,900,000	
Total Permanent Investment - Unadjusted		$ 794,000,000
Site Factor		1.00
Total Permanent Investment		**$ 794,000,000**

21.3. Allam Cycle Total Permanent Investment

Table 21.4: Total Permanent Investment for the Allam Cycle

Investment Summary		
Installed Equipment Costs:		
Total:		**$ 594,000,000**
Direct Permanent Investment		
Cost of Site Preparations:	$ 29,700,000	
Cost of Service Facilities:	$ 29,700,000	
Allocated Costs for utility plants and related facilities:	$ -	
Direct Permanent Investment		**$ 653,000,000**
Total Depreciable Capital		
Cost of Contingencies & Contractor Fees	$ 118,000,000	
Total Depreciable Capital		**$ 771,000,000**
Total Permanent Investment		
Cost of Land:	$ 15,000,000	
Cost of Royalties:	$ -	
Cost of Plant Start-Up:	$ 77,100,000	
Total Permanent Investment - Unadjusted		$ 863,000,000
Site Factor		1.00
Total Permanent Investment		**$ 863,000,000**

Operating Cost – Cost of Manufacture

22.1. Raw Materials

Natural gas is the primary feedstock for all 3 cases. As shown in Section 14, the price is expected to rise consistent with the cost of electricity. There is much larger sensitivity to the CO_2 credit, whereas the margin between electricity and natural gas cost will vary similarly for all three cases. Therefore, the cost of natural gas and sale of electricity are assumed to be constant at $2.60/MMBtu and $60/MW-hr, respectively. Given the HHV efficiency, the raw material costs for natural gas can be calculated.

22.2. NGCC Utilities

The NGCC has a cooling water requirement of 174,880 gpm for the condenser and boiler feed water requirement of 1965 gpm in the Rankine cycle. Case 2 with CDR requires an additional 4748 gpm of cooling water in the CO_2 compressor intercoolers, and 414 tons/day of chilled water at 40^{o}F for the pipeline CO2 cooler.

The costs of cooling water, boiler feed water, and chilled water are $0.10/1,000-gal, $2.00/1,000-gal, and $1.50/ton-day, as shown in Table 17.1 of Seider et al. [19].

22.3. Allam Cycle Utilities

The natural gas and CO_2 compressors require 1,290 MMBtu/hr of cooling. Assuming cooling water enters the intercoolers at 90 ^{o}F and leaves at 120 ^{o}F, 85,761 gpm of cooling water is required. There is an additional 20,000 gpm for the MAC and BAC and 48,624 gpm for Cooler1 and Cooler3, for a total of 154,385 gpm of cooling water.

22.4. Other Variable Costs

Other variable costs were assumed to be default values, according to Chapter 17 of Seider et al. and are shown in Table 22.1. The default operating factor of 0.904 is assumed. Each plant will require one year for design one year for construction and operate for 20 years. The current tax law 45Q only permits the CO_2 credit to be received for 12 years, but it is assumed the credit is extended to the 20-year lifetime.

Table 22.1 Other Variable Cost Assumptions

Other Variable Costs		
General Expenses		
Selling / Transfer Expenses:	3.00%	of Sales
Direct Research:	4.80%	of Sales
Allocated Research:	0.50%	of Sales
Administrative Expense:	2.00%	of Sales
Management Incentive Compensation:	1.25%	of Sales

22.5. Fixed Costs

For fixed costs from operations, the Allam cycle and NGCC with CDR are estimated to require 6 operators per shift, while the NGCC without CDR requires 4 operators per shift. There was assumed to be 5 shifts with salaries of $40/operator hour. Technical assistance to manufacturing was estimated to be $400,000/year, equivalent to two engineers, and the control laboratory was estimated to be equivalent to one engineer, or $200,000/year. Costs for operating salaries and benefits and operating and supplies and services were estimated using default values as a percentage of direct wages and benefits.

Other fixed costs for maintenance, operating overhead, and property taxes and insurances were taken as default from the Profitability Analysis spreadsheet. The assumptions for the total fixed costs are shown in Table 22.2.

Table 22.2: Fixed Costs Assumptions

Fixed Costs		
Operations		
Operators per Shift:	6	(4 operators for NGCC without CDR)
Number of shifts	5	shifts
Direct Wages and Benefits:	$40	/operator hour
Direct Salaries and Benefits:	15%	of Direct Wages and Benefits
Operating Supplies and Services:	6%	of Direct Wages and Benefits
Technical Assistance to Manufacturing:	$400,000	per year
Control Laboratory:	$200,000	per year
Maintenance		
Wages and Benefits:	3.50%	of Total Depreciable Capital
Salaries and Benefits:	25.00%	of Maintenance Wages and Benefits
Materials and Services:	100.00%	of Maintenance Wages and Benefits
Maintenance Overhead:	5.00%	of Maintenance Wages and Benefits
Operating Overhead		
General Plant Overhead:	7.10%	of Maintenance and Operations Wages and Benefits
Mechanical Department Services:	2.40%	of Maintenance and Operations Wages and Benefits
Employee Relations Department	5.90%	of Maintenance and Operations Wages and Benefits
Business Services	7.40%	of Maintenance and Operations Wages and Benefits
Property Taxes and Insurance		
Property Taxes and Insurance:	2.00%	of Total Depreciable Capital

22.6. Working Capital

Table 22.3 shows the working capital assumptions. All values were taken as default from the Profitability Analysis spreadsheet, except for the inventory and raw materials which were removed due to the continuous pipeline operations and electricity production.

Table 22.3 Working Capital Assumptions

Working Capital		
Accounts Receivable	8.33%	of sales
Cash Reserves (excluding Raw Materials)	8.33%	of COM
Accounts Payable	8.33%	of feedstock cost

22.7. Summary of NGCC and NGCC with CDR Sales and Costs

Table 22.4 summarizes the earnings before depreciation and taxes for the NGCC at 90% capacity.

Table 22.4: NGCC Earnings Before Taxes and Depreciation (90% capacity)

	$/year	$/MW-hr
Sales	$ 137,820,000	$ 60
General Expenses	$ (15,920,000)	$ (6.9)
Natural Gas	$ (55,560,000)	$ (24)
Cooling Water	$ (7,480,000)	$ (3.3)
Chilled Water	$ -	$ -
Boiler Feed Water	$ (1,680,000)	$ (0.7)
Operations	$ (3,620,000)	$ (1.6)
Maintenance	$ (27,730,000)	$ (12)
Operating Overhead	$ (3,320,000)	$ (1.4)
Property Taxes and Insurance	$ (6,890,000)	$ (3.0)
Earrnings Before Taxes & Depreciation	**$ 15,630,000**	**$ 6.8**

Table 22.5 summarizes the sales and costs before depreciation, taxes, and CO_2 credit for the NGCC with CDR at 90% capacity.

Table 22.5: NGCC with CDR Earnings Before Taxes and Depreciation (90% capacity)

	$/year	$/MW-hr
Sales	$ 128,290,000	$ 60
General Expenses	$ (14,820,000)	$ (6.9)
Natural Gas	$ (55,630,000)	$ (26)
Cooling Water	$ (7,680,000)	$ (3.6)
Chilled Water	$ (180,000)	$ (0.1)
Boiler Feed Water	$ (1,680,000)	$ (0.8)
Operations	$ (3,620,000)	$ (1.7)
Maintenance	$ (57,080,000)	$ (27)
Operating Overhead	$ (6,230,000)	$ (2.9)
Property Taxes and Insurance	$ (14,180,000)	$ (6.6)
Earrnings Before Taxes & Depreciation	**$ (32,810,000)**	**$ (15)**

22.8. Summary of Allam Cycle Sales and Costs

Table 22.6 summarizes the sales and costs before depreciation, taxes, and CO_2 credit for the Allam Cycle at 90% capacity.

Table 22.6: Allam Cycle Earnings Before Taxes and Depreciation (90% capacity)

	$/year	**$/MW-hr**
Sales	$ 128,290,000	$ 60
General Expenses	$ (14,820,000)	$ (6.9)
Natural Gas	$ (54,660,000)	$ (26)
Cooling Water	$ (6,600,000)	$ (3.1)
Chilled Water	$ -	$ -
Boiler Feed Water	$ -	$ -
Operations	$ (3,620,000)	$ (1.7)
Maintenance	$ (62,050,000)	$ (29)
Operating Overhead	$ (6,720,000)	$ (3.1)
Property Taxes and Insurance	$ (15,420,000)	$ (7.2)
Earrnings Before Taxes & Depreciation	**$ (35,600,000)**	**$ (17)**

Profitability Analysis – Business Case

Figures 23.1, 23.2, and 23.3 summarize the discounted cash flow and net present value at a cost of capital of 15% for the NGCC, NGCC with CDR, and Allam cycle, respectively. It is assumed that a large utility company with existing earnings can use the full extent of the operating loss as a tax credit.

23.1. NGCC Profitability Analysis

Figure 23.1: Cash Flow Summary for the NGCC

Year	Percentage of Design Capacity	Electricity Price ($/MW-hr)	Sales	Capital Costs	Working Capital	Var Costs	Fixed Costs	Total Costs	15 Year MACRS	Depreciation	Taxible Income	Taxes	CO2 Credit ($/tonne CO2)	CO2 Credit	Net Earnings	Cash Flow	Cumulative Net Present Value
2022	0%	$60.00	-	-	-	-	-	-		-	-	-	$ -	-	-	-	-
2023	0%	$60.00	-	(384,388,645)	(7,240,678)	-	-	-		-	-	-	$ -	-	-	(391,629,323)	(340,547,237)
2024	45%	$60.00	68,912,278	-	(3,620,339)	(40,317,496)	(40,023,618)	(80,341,114)	5.00%	(17,160,207)	(28,589,043)	6,575,480	$ -	-	(22,013,563)	(8,473,695)	(346,954,568)
2025	68%	$60.00	103,368,417	-	(3,620,339)	(60,476,244)	(40,023,618)	(100,499,862)	9.50%	(32,604,394)	(29,735,839)	6,839,243	$ -	-	(22,896,596)	6,087,459	(342,951,965)
2026	90%	$60.00	137,824,556	-	-	(80,634,992)	(40,023,618)	(120,658,609)	8.55%	(29,343,955)	(12,178,008)	2,800,942	$ -	-	(9,377,066)	19,966,888	(331,535,832)
2027	90%	$60.00	137,824,556	-	-	(80,634,992)	(40,023,618)	(120,658,609)	7.70%	(26,426,719)	(9,260,773)	2,129,978	$ -	-	(7,130,795)	19,295,924	(321,942,347)
2028	90%	$60.00	137,824,556	-	-	(80,634,992)	(40,023,618)	(120,658,609)	6.93%	(23,784,047)	(6,618,101)	1,522,163	$ -	-	(5,095,938)	18,688,110	(313,862,961)
2029	90%	$60.00	137,824,556	-	-	(80,634,992)	(40,023,618)	(120,658,609)	6.23%	(21,381,618)	(4,215,672)	969,605	$ -	-	(3,246,067)	18,135,551	(307,045,136)
2030	90%	$60.00	137,824,556	-	-	(80,634,992)	(40,023,618)	(120,658,609)	5.90%	(20,249,045)	(3,083,098)	709,113	$ -	-	(2,373,986)	17,875,059	(301,201,748)
2031	90%	$60.00	137,824,556	-	-	(80,634,992)	(40,023,618)	(120,658,609)	5.90%	(20,249,045)	(3,083,098)	709,113	$ -	-	(2,373,986)	17,875,059	(296,120,540)
2032	90%	$60.00	137,824,556	-	-	(80,634,992)	(40,023,618)	(120,658,609)	5.91%	(20,283,365)	(3,117,419)	717,006	$ -	-	(2,400,412)	17,882,953	(291,700,148)
2033	90%	$60.00	137,824,556	-	-	(80,634,992)	(40,023,618)	(120,658,609)	5.90%	(20,249,045)	(3,083,098)	709,113	$ -	-	(2,373,986)	17,875,059	(287,858,025)
2034	90%	$60.00	137,824,556	-	-	(80,634,992)	(40,023,618)	(120,658,609)	5.91%	(20,283,365)	(3,117,419)	717,006	$ -	-	(2,400,412)	17,882,953	(284,515,573)
2035	90%	$60.00	137,824,556	-	-	(80,634,992)	(40,023,618)	(120,658,609)	5.90%	(20,249,045)	(3,083,098)	709,113	$ -	-	(2,373,986)	17,875,059	(281,610,376)
2036	90%	$60.00	137,824,556	-	-	(80,634,992)	(40,023,618)	(120,658,609)	5.91%	(20,283,365)	(3,117,419)	717,006	$ -	-	(2,400,412)	17,882,953	(279,083,003)
2037	90%	$60.00	137,824,556	-	-	(80,634,992)	(40,023,618)	(120,658,609)	5.90%	(20,249,045)	(3,083,098)	709,113	$ -	-	(2,373,986)	17,875,059	(276,886,256)
2038	90%	$60.00	137,824,556	-	-	(80,634,992)	(40,023,618)	(120,658,609)	5.91%	(20,283,365)	(3,117,419)	717,006	$ -	-	(2,400,412)	17,882,953	(274,975,199)
2039	90%	$60.00	137,824,556	-	-	(80,634,992)	(40,023,618)	(120,658,609)	2.95%	(10,124,522)	7,041,424	(1,619,528)	$ -	-	5,421,897	15,546,419	(273,530,534)
2040	90%	$60.00	137,824,556	-	-	(80,634,992)	(40,023,618)	(120,658,609)	0.00%	-	17,165,947	(3,948,168)	$ -	-	13,217,779	13,217,779	(272,462,470)
2041	90%	$60.00	137,824,556	-	-	(80,634,992)	(40,023,618)	(120,658,609)	0.00%	-	17,165,947	(3,948,168)	$ -	-	13,217,779	13,217,779	(271,533,718)
2042	90%	$60.00	137,824,556	-	-	(80,634,992)	(40,023,618)	(120,658,609)	0.00%	-	17,165,947	(3,948,168)	$ -	-	13,217,779	13,217,779	(270,726,108)
2043	90%	$60.00	137,824,556	-	14,481,356	(80,634,992)	(40,023,618)	(120,658,609)	0.00%	-	17,165,947	(3,948,168)	$ -	-	13,217,779	27,699,135	(269,254,435)

23.2. NGCC with CDR Profitability Analysis

Figure 23.2: Cash Flow Summary for NGCC with CDR

Year	Percentage of Design Capacity	Electricity Price ($/MW-hr)	Sales	Capital Costs	Working Capital	Var Costs	Fixed Costs	Total Costs	15 Year MACRS	Depreciation	Taxible Income	Taxes	CO2 Credit ($/tonne CO2)	CO2 Credit	Net Earnings	Cash Flow	Cumulative Net Present Value
2022	0%	$60.00	-	-	-	-	-	-		-	-	-	$ -	-	-	-	-
2023	0%	$60.00	-	(793,623,891)	(8,373,971)	-	-	-		-	-	-	$ -	-	-	(801,997,862)	(697,389,445)
2024	45%	$60.00	64,144,224	-	(4,186,985)	(39,994,784)	(81,057,391)	(121,052,175)	5.00%	(35,429,638)	(92,337,589)	21,237,645	$ 43	21,926,135	(49,173,808)	(17,931,156)	(710,947,975)
2025	68%	$60.00	96,216,336	-	(4,186,985)	(59,992,176)	(81,057,391)	(141,049,567)	9.50%	(67,316,312)	(112,149,543)	25,794,395	$ 47	35,424,396	(50,930,752)	12,198,575	(702,927,214)
2026	90%	$60.00	128,288,448	-	-	(79,989,568)	(81,057,391)	(161,046,959)	8.55%	(60,584,681)	(93,343,192)	21,468,934	$ 50	50,602,666	(21,271,592)	39,313,089	(680,449,828)
2027	90%	$60.00	128,288,448	-	-	(79,989,568)	(81,057,391)	(161,046,959)	7.70%	(54,561,643)	(87,320,153)	20,083,635	$ 50	50,602,666	(16,633,852)	37,927,790	(661,593,013)
2028	90%	$60.00	128,288,448	-	-	(79,989,568)	(81,057,391)	(161,046,959)	6.93%	(49,105,478)	(81,863,989)	18,828,717	$ 50	50,602,666	(12,432,606)	36,672,872	(645,738,318)
2029	90%	$60.00	128,288,448	-	-	(79,989,568)	(81,057,391)	(161,046,959)	6.23%	(44,145,329)	(76,903,840)	17,687,883	$ 50	50,602,666	(8,613,291)	35,532,038	(632,380,509)
2030	90%	$60.00	128,288,448	-	-	(79,989,568)	(81,057,391)	(161,046,959)	5.90%	(41,806,973)	(74,565,484)	17,150,061	$ 50	50,602,666	(6,812,757)	34,994,216	(620,940,838)
2031	90%	$60.00	128,288,448	-	-	(79,989,568)	(81,057,391)	(161,046,959)	5.90%	(41,806,973)	(74,565,484)	17,150,061	$ 50	50,602,666	(6,812,757)	34,994,216	(610,993,298)
2032	90%	$60.00	128,288,448	-	-	(79,989,568)	(81,057,391)	(161,046,959)	5.91%	(41,877,832)	(74,636,343)	17,166,359	$ 50	50,602,666	(6,867,318)	35,010,514	(602,339,234)
2033	90%	$60.00	128,288,448	-	-	(79,989,568)	(81,057,391)	(161,046,959)	5.90%	(41,806,973)	(74,565,484)	17,150,061	$ 50	50,602,666	(6,812,757)	34,994,216	(594,817,464)
2034	90%	$60.00	128,288,448	-	-	(79,989,568)	(81,057,391)	(161,046,959)	5.91%	(41,877,832)	(74,636,343)	17,166,359	$ 50	50,602,666	(6,867,318)	35,010,514	(588,273,749)
2035	90%	$60.00	128,288,448	-	-	(79,989,568)	(81,057,391)	(161,046,959)	5.90%	(41,806,973)	(74,565,484)	17,150,061	$ 50	50,602,666	(6,812,757)	34,994,216	(582,586,211)
2036	90%	$60.00	128,288,448	-	-	(79,989,568)	(81,057,391)	(161,046,959)	5.91%	(41,877,832)	(74,636,343)	17,166,359	$ 50	50,602,666	(6,867,318)	35,010,514	(577,638,222)
2037	90%	$60.00	128,288,448	-	-	(79,989,568)	(81,057,391)	(161,046,959)	5.90%	(41,806,973)	(74,565,484)	17,150,061	$ 50	50,602,666	(6,812,757)	34,994,216	(573,337,626)
2038	90%	$60.00	128,288,448	-	-	(79,989,568)	(81,057,391)	(161,046,959)	5.91%	(41,877,832)	(74,636,343)	17,166,359	$ 50	50,602,666	(6,867,318)	35,010,514	(569,596,235)
2039	90%	$60.00	128,288,448	-	-	(79,989,568)	(81,057,391)	(161,046,959)	2.95%	(20,903,486)	(53,661,997)	12,342,259	$ 50	50,602,666	9,282,928	30,186,414	(566,791,136)
2040	90%	$60.00	128,288,448	-	-	(79,989,568)	(81,057,391)	(161,046,959)	0.00%	-	(32,758,511)	7,534,457	$ 50	50,602,666	25,378,612	25,378,612	(564,740,414)
2041	90%	$60.00	128,288,448	-	-	(79,989,568)	(81,057,391)	(161,046,959)	0.00%	-	(32,758,511)	7,534,457	$ 50	50,602,666	25,378,612	25,378,612	(562,957,178)
2042	90%	$60.00	128,288,448	-	-	(79,989,568)	(81,057,391)	(161,046,959)	0.00%	-	(32,758,511)	7,534,457	$ 50	50,602,666	25,378,612	25,378,612	(561,406,537)
2043	90%	$60.00	128,288,448	-	16,747,941	(79,989,568)	(81,057,391)	(161,046,959)	0.00%	-	(32,758,511)	7,534,457	$ 50	50,602,666	25,378,612	42,126,554	(559,168,325)

23.3. Allam Cycle Profitability Analysis

Figure 23.3: Cash Flow Summary for Allam Cycle

Year	Percentage of Design Capacity	Electricity Price ($/MW-hr)	Sales	Capital Costs	Working Capital	Var Costs	Fixed Costs	Total Costs	15 year MACRS	Depreciation	Taxible Income	Taxes	CO2 Credit ($/tonne CO2)	CO2 Credit	Net Earnings	Cash Flow	Cumulative Net Present Value
2022	0%	$60.00	-	-	-	-	-	-		-	-	-	$ -	-	-	-	-
2023	0%	$60.00	-	(863,246,267)	(8,634,427)	-	-	-		-	-	-	$ -	-	-	(871,880,694)	(758,157,125)
2024	45%	$60.00	64,144,224	-	(4,317,214)	(38,041,498)	(87,800,815)	(125,842,313)	5.00%	(38,537,780)	(100,235,869)	23,054,250	$ 50	27,439,474	(49,742,146)	(15,521,580)	(769,893,669)
2025	68%	$60.00	96,216,336	-	(4,317,214)	(57,062,247)	(87,800,815)	(144,863,062)	9.50%	(73,221,782)	(121,868,508)	28,029,757	$ 50	41,159,210	(52,679,541)	16,225,027	(759,225,451)
2026	90%	$60.00	128,288,448	-	-	(76,082,997)	(87,800,815)	(163,883,812)	8.55%	(65,899,603)	(101,494,967)	23,343,842	$ 50	54,878,947	(23,272,177)	42,627,426	(734,853,082)
2027	90%	$60.00	128,288,448	-	-	(76,082,997)	(87,800,815)	(163,883,812)	7.70%	(59,348,181)	(94,943,544)	21,837,015	$ 50	54,878,947	(18,227,582)	41,120,599	(714,408,877)
2028	90%	$60.00	128,288,448	-	-	(76,082,997)	(87,800,815)	(163,883,812)	6.93%	(53,413,363)	(89,008,726)	20,472,007	$ 50	54,878,947	(13,657,772)	39,755,591	(697,221,438)
2029	90%	$60.00	128,288,448	-	-	(76,082,997)	(87,800,815)	(163,883,812)	6.23%	(48,018,074)	(83,613,437)	19,231,091	$ 50	54,878,947	(9,503,399)	38,514,674	(682,742,345)
2030	90%	$60.00	128,288,448	-	-	(76,082,997)	(87,800,815)	(163,883,812)	5.90%	(45,474,580)	(81,069,944)	18,646,087	$ 50	54,878,947	(7,544,909)	37,929,671	(670,343,068)
2031	90%	$60.00	128,288,448	-	-	(76,082,997)	(87,800,815)	(163,883,812)	5.90%	(45,474,580)	(81,069,944)	18,646,087	$ 50	54,878,947	(7,544,909)	37,929,671	(659,561,089)
2032	90%	$60.00	128,288,448	-	-	(76,082,997)	(87,800,815)	(163,883,812)	5.91%	(45,551,656)	(81,147,019)	18,663,814	$ 50	54,878,947	(7,604,258)	37,947,398	(650,181,072)
2033	90%	$60.00	128,288,448	-	-	(76,082,997)	(87,800,815)	(163,883,812)	5.90%	(45,474,580)	(81,069,944)	18,646,087	$ 50	54,878,947	(7,544,909)	37,929,671	(642,028,347)
2034	90%	$60.00	128,288,448	-	-	(76,082,997)	(87,800,815)	(163,883,812)	5.91%	(45,551,656)	(81,147,019)	18,663,814	$ 50	54,878,947	(7,604,258)	37,947,398	(634,935,707)
2035	90%	$60.00	128,288,448	-	-	(76,082,997)	(87,800,815)	(163,883,812)	5.90%	(45,474,580)	(81,069,944)	18,646,087	$ 50	54,878,947	(7,544,909)	37,929,671	(628,771,075)
2036	90%	$60.00	128,288,448	-	-	(76,082,997)	(87,800,815)	(163,883,812)	5.91%	(45,551,656)	(81,147,019)	18,663,814	$ 50	54,878,947	(7,604,258)	37,947,398	(623,408,020)
2037	90%	$60.00	128,288,448	-	-	(76,082,997)	(87,800,815)	(163,883,812)	5.90%	(45,474,580)	(81,069,944)	18,646,087	$ 50	54,878,947	(7,544,909)	37,929,671	(618,746,673)
2038	90%	$60.00	128,288,448	-	-	(76,082,997)	(87,800,815)	(163,883,812)	5.91%	(45,551,656)	(81,147,019)	18,663,814	$ 50	54,878,947	(7,604,258)	37,947,398	(614,691,433)
2039	90%	$60.00	128,288,448	-	-	(76,082,997)	(87,800,815)	(163,883,812)	2.95%	(22,737,290)	(58,332,654)	13,416,510	$ 50	54,878,947	9,962,804	32,700,094	(611,652,747)
2040	90%	$60.00	128,288,448	-	-	(76,082,997)	(87,800,815)	(163,883,812)	0.00%	-	(35,595,364)	8,186,934	$ 50	54,878,947	27,470,517	27,470,517	(609,432,989)
2041	90%	$60.00	128,288,448	-	-	(76,082,997)	(87,800,815)	(163,883,812)	0.00%	-	(35,595,364)	8,186,934	$ 50	54,878,947	27,470,517	27,470,517	(607,502,764)
2042	90%	$60.00	128,288,448	-	-	(76,082,997)	(87,800,815)	(163,883,812)	0.00%	-	(35,595,364)	8,186,934	$ 50	54,878,947	27,470,517	27,470,517	(605,824,308)
2043	90%	$60.00	128,288,448	-	17,268,855	(76,082,997)	(87,800,815)	(163,883,812)	0.00%	-	(35,595,364)	8,186,934	$ 50	54,878,947	27,470,517	44,739,372	(603,447,275)

23.4. Breakeven CO_2 Credit

Figures 23.2 and 23.3 include an after-tax carbon credit of $50/tonne. While under the current policy of tax code 45Q, the credit increases from $43/tonne in 2024 to $50/tonne in 2026 and ends after the twelfth year, it is obvious by the lower NPV compared to case 1 that an increased credit is needed to make economic sense. Therefore, the base case assumes the $50/tonne credit is extended for the lifetime of the project. Appendix 28.24 shows the cash flow analysis according to the current tax code of a ramp up to $50/tonne and 12-year limit. Under the current 45Q code, the NPV for the Allam cycle at a cost of capital of 15% is -$648MM.

At a credit of $50/tonne of CO2, the NGCC with CDR has a negative net present value and is less economical than the NGCC but more economical than the Allam cycle. If the CO_2 credit were to rise to $121/tonne, the NGCC with CDR would have an equivalent NPV as the NGCC without CDR. However, for a less established process such as this, a 15% IRR is generally desired with the associated risk. The breakeven CO_2 credit for a 15% IRR is $188/tonne.

For the Allam cycle, a $112/tonne credit is required to break even with the NGCC without CDR, and a $163/tonne credit is required for a 15% IRR. The Allam cycle, while less economical than the traditional NGCC with CDR under today's tax code, proves to benefit more with increasing tax credit, as over 99% of the carbon dioxide can be recovered.

23.5. Other Economic Considerations

Two other scenarios can increase the attractiveness of the Allam cycle. One is the potential sale of high purity nitrogen. Given the fixed boundary conditions to effectively compare the Allam cycle and NGCC, nitrogen distribution was not considered, but it is a potential revenue stream.

Lastly, a CO_2 capture credit was analyzed, but there is also the potential for a negative externality tax on carbon emissions. Legislation efforts have failed in the US, but a carbon tax has been implemented in some countries in Europe. Given that the traditional NGCC captures no CO_2 and the amine scrubbing system has only been developed to large scales at 90% recovery, the Allam cycle would become increasingly attractive with a negative externality tax.

Assuming no nearby demand for high purity nitrogen, no negative externality tax, constant natural gas and electricity prices, and a carbon credit extending for the lifetime of the project, Figure 23.4 summarizes the NPV for all three cases as a function of carbon credit. Many carbon capture projects such as the Allam cycle receive one-time startup grants from the DOE or other organizations. These grants enter the cash flow analysis directly in the first year of operation and have no subsequent effect, so the difference in NPV between two cases can be viewed as the necessary grant amount which would make the investments equivalent.

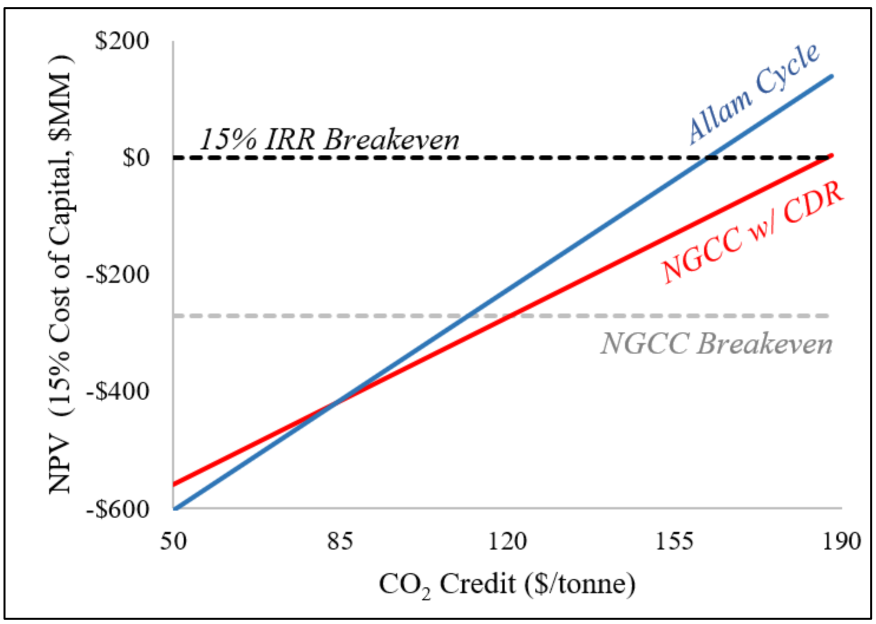

Figure 23.4: NPV for 3 cases as a function of carbon dioxide credit.

Other Important Considerations

24.1. Environmental Considerations

While the Allam cycle sequesters over 99% of the CO_2 produced from combustion of natural gas, that is only within the battery limits of the plant. The sourcing of natural gas has associated greenhouse gas leakage that must be considered in a full life cycle assessment (LCA), and the manufacturing of steel and concrete for construction will have associated emissions.

With any fossil fuel combustion plant, there is potential for SO_x and NO_x emissions, which were also not considered in this project. The Cansolv amine scrubbing technology does have the ability to also absorb SO_2, although it was not considered in this report. The low amount of N_2 in oxyfuel combustion would also lessen NO_x formation.

24.2. Social Considerations

With any carbon capture or green technology, there is an associated moral hazard of permitting a 'business as usual' philosophy. The Allam cycle and NGCC with CDR can capture CO_2 from the combusted natural gas, but they are not net-negative technologies. In order to prevent global temperatures from rising above 1.5^{o}C, additional technologies will be needed, and the Allam cycle, or any other single technology, should not be viewed as a one-step solution.

24.3. Safety Considerations

Both cycles operate at temperatures above 2000^{o}F, and safety must remain a top priority. Given the established technology, safety protocols are well-documented and must always be followed closely.

Conclusions and Recommendations

25.1. Conclusions and Recommendations

The Allam cycle was compared to the industry standard natural gas combined cycle (NGCC) and NGCC with carbon dioxide removal (CDR). The powerplants were modeled in Aspen Plus, and a comparative analysis of OPEX and CAPEX was conducted.

Under current US tax code, it is not advised to invest in the Allam cycle from an economic perspective. Three scenarios, however, could increase the viability of the Allam cycle.

The first scenario, directly analyzed in this report, is an increase in the CO_2 credit in tax code 45Q from $50/tonne to $112/tonne, which is the break-even credit to be equivalent with the traditional NGCC, or $163/tonne for an IRR of 15%. This also assumes the credit would be extended for the entire life of the project, from the 12-year time frame currently in place. The NPV of the Allam cycle is also lower than that of the NGCC with CDR, but the NGCC with CDR breakeven credits are $121/tonne to be equivalent to the traditional NGCC and $188/tonne for a 15% IRR.

Although the Allam cycle has a lower NPV than the NGCC with CDR under the current base case conditions, the Allam cycle benefits more from an increase in tax credit since it captures over 99% of the carbon dioxide, compared to 90% in real post-combustion capture units. The key parameter is the breakeven credits to the traditional NGCC of $112/tonne vs. $121/tonne. There is an extensive list of sensitivities that could be done on performance assumptions, electricity costs, raw materials, and other variables not exhausted in this report that could influence the IRR in absolute terms for each scenario. However, the scale of NGCC capacity added in the last decade is indicative of its financial and operating performance, and determination of the breakeven credit is deemed to be a significant metric in this analysis. Given the trend in sequestration credits since 2016, a revision to 45Q is possible, and these breakeven credits should be considered and revised as the technology and policy further develops.

The second scenario relies on capitalization of the high purity N_2 stream produced in the integrated air separation unit, which is not a possibility for the NGCC. It was assumed in this report that the high purity nitrogen stream was vented to the atmosphere.

Third, there is increasing focus on reducing the carbon footprint of the energy sector, and economic vehicles beyond a simple sequestration credit could be implemented. A negative externality on carbon emissions would reduce the break-even credit for the Allam cycle. Furthermore, companies outside of the energy sector seeking to become carbon neutral could benefit two-fold from the operation losses to offset taxes and the after-tax credit from 45Q.

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We are grateful for the guidance of our project author, Adam Brostow, who provided countless email responses and attended each weekly meeting. We also would like to thank Professor Seider for ensuring a timely and successful completion of the project. Thank you to Professor Fabiano for guiding us through Aspen Plus and offering stories and positivity along the way. We also would like to thank Bruce Vrana for providing thorough responses at any time of the day and despite any number of conflicts. Lastly, thank you to the entire industrial consultant team for your help in completion of this project. We could not have done it without all of your help.

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Appendix

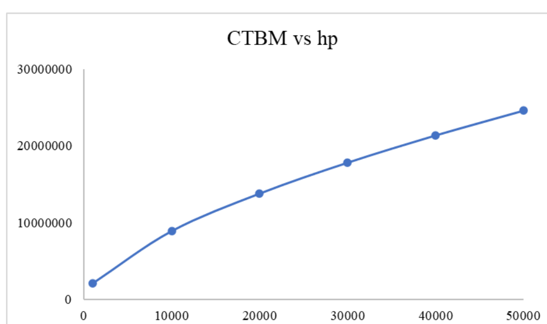
28.1. Compressors

Compressors	*Source: Equip Design Spreadsheet included in Seider et al*							
FBM =	2.15		CE =	600				
Name	Compressor Type	Pc	Cb	FD	FM	Cp	Cp	CBM
	(screw, centrifugal, reciprocating)	*hp*	*$(CE=567)*	*see below*	*see below*	*$ (CE=567)*	*$ (Given CE)*	*$ (Given CE)*
Natural Gas Compressor	Centrifugal Compressor	10047	3143252	1.25	1	3929065	**$ 4,157,741**	8939143
CO2 Compressor	Centrifugal Compressor	47705	8386708	1.25	1	10483385	**$ 11,093,529**	23851088
Main Air Compressor	Centrifugal Compressor	24933	5572682	1.25	1	6965852	**$ 7,371,272**	15848235
Booster Air Compressor	Centrifugal Compressor	32535	6589877	1.25	1	8237346	**$ 8,716,768**	18741051

Allam Cycle

Name	Compressor Type	Pc	Cb	FD	FM	Cp	Cp	CBM
	(screw, centrifugal, reciprocating)	*hp*	*$(CE=567)*	*see below*	*see below*	*$ (CE=567)*	*$ (Given CE)*	*$ (Given CE)*
NG Comp	Reciprocating Compressor	1004	528421	1.25	1	660527	**$ 698,970**	1502785
CO2 Comp	Centrifugal Compressor	17089.5	4392540	1.15	1	5051421	**$ 5,345,420**	11492652

NGCC



Extrapolation past 30,000hp is assumed to be okay.

28.2. Gas Turbine

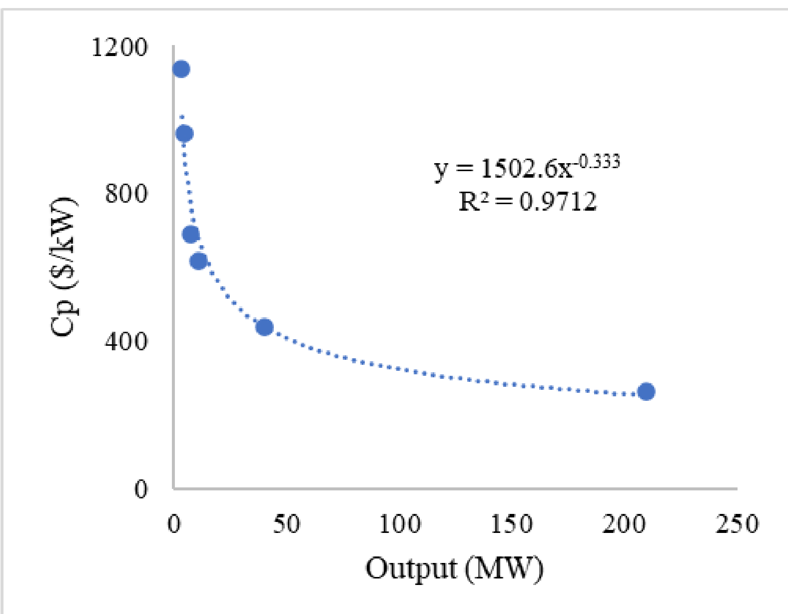
Data from [12] and [20], and Allam Cycle cost calculation:

Net Output (MW)	Cp ($/kW)	CTBM ($/kW)	Total Investment ($/kW)	Source	
3.30	1137	2274	**3320**	DOE: https://www.energy.gov/sites/prod/files/2016/09/f33/CHP-Gas%20Turbine.pdf	"Installed capital costs vary significantly depending on the scope of the plant equipment, geographical area, competitive market conditions, special site requirements, emissions control requirements, and prevailing labor rates" **this is assumed to be our CTPI**
4.32	965	1930	**2817**		
7.49	691	1382	**2017**		
10.67	616	1232	**1798**		
40.49	437	874	**1276**		
210	**266**	532	777	DOE/NETL, GE F-Class Turbine	**Explicitly gives purchase price**

turbine output:	***614.2***				
Compressor req:	***265.1***		***Allam Cycle***		
net output (all 4):	***349.1***				
	Output	Cp ($/kW)	Cp	FBM	CTBM
4 in parallel	87.3	$ 339	**$ 29,608,535**	2	$ 59,217,070

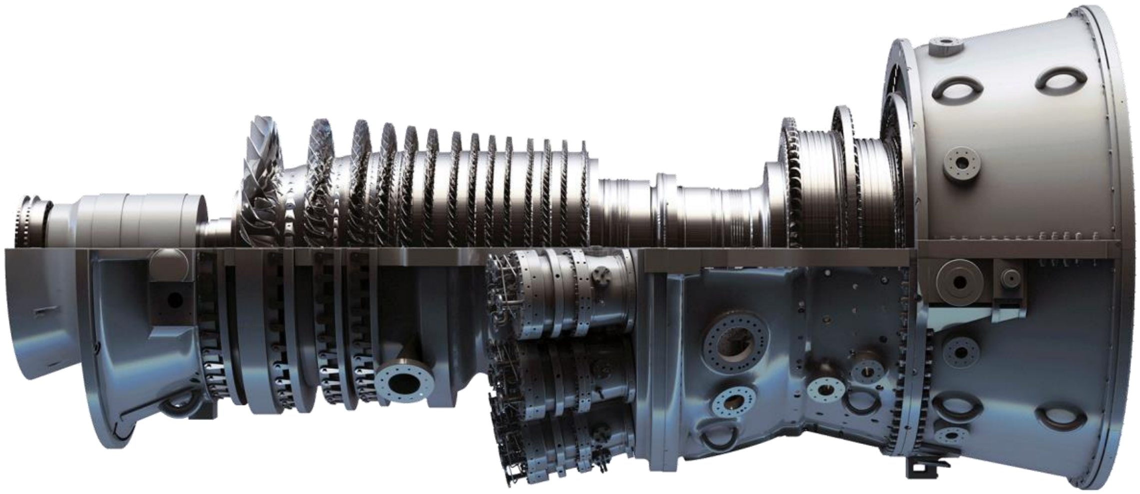
NGCC (same correlation as Allam Cycle):

net output	***232.5***		***NGCC***		
	Output	Cp ($/kW)	Cp	FBM	CTBM
2 in paralle	*116.25*	$ 308	**$ 35,847,633**	2	$ 71,695,267



Correlation derived from [12] and [20] for gas turbine cost as function of net output

GE F-Class Turbine [22]:



Air compressor *Combustion* *Turbine/Expander*

28.3. HRSG

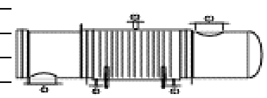
Heat Exchanger Specification Sheet

Company:								
Location:								
Service of Unit:	Our Reference:							
Item No.:	Your Reference:							
Date:	Rev No.:	Job No.:						
Size	93 -	186 in	Type	AIM	Hor	Connected in	10 parallel	2 series
Surf/unit(eff.)	324918	ft²	Shells/unit	20		Surf/shell (eff.)	16245.9	ft²

PERFORMANCE OF ONE UNIT

Fluid allocation		Shell Side		Tube Side	
FluidName		Water		Combustion Gas	
Fluid quantity, Total	lb/h	965794		6559042	
Vapor (In/Out)	lb/h	0	965794	6559042	6559042
Liquid	lb/h	965794	0	0	0
Noncondensable	lb/h	0		0	
Temperature (In/Out)	°F	100.3	855.56	1173.64	400.06
Bubble / Dew point	C	448.46 / 448.46	448.28 / 448.28	/	/
Density (Vap / Liq)	lb/ft³	/ 62.129	0.545 /	0.04 /	0.055 /
Viscosity	cp	/ 0.6792	0.027 /	0.0396 /	0.0255 /
Molecular wt, Vap			18.01	28.33	28.33
Molecular wt, NC					
Specific heat	BTU/(lb-F)	/ 1.0003	0.5282 /	0.2854 /	0.2592 /
Thermal conductivity	BTU/(ft-h-F)	/ 0.357	0.038 /	0.037 /	0.021 /
Latent heat	BTU/lb	780.4	780.6		
Pressure (abs)	psi	414.7	413.9	24.7	18.03
Velocity (Mean/Max)	ft/s	2.66 /	8.49	271.84 /	324.44
Pressure drop, allow./calc.	psi	20	0.79	10	6.66
Fouling resistance (min)	ft²-h-F/BTU	0.0005		0.0005 0.0006	Ao based
Heat exchanged	1353523070 BTU/h		MTD corrected		233.94 °F
Transfer rate, Service	17.81	Dirty	25.07 Clean	25.76	BTU/(h-ft²-F)

CONSTRUCTION OF ONE SHELL　　　　**Sketch**



			Shell Side				Tube Side			
Design/vac/test pressure:g		psi	460	/	/		50	/	/	
Design temperature / MDMT		°F	920	/			1240	/		
Number passes per shell			1				1			
Corrosion allowance		in	0.0625				0.0625			
Connections	In	in	2	3	/	-	1	54	/	-
Size/rating	Out		2	8	/	-	1	52	/	-
Nominal	Intermediate		1	8	/	-	1	54	/	-

Tube No.	6068	OD 0.75	Tks- Avg 0.049 in	Length 186 in		Pitch 0.9375 in		
Tubetype	Plain		#/in	Material	Carbon Steel	Tube pattern	90	
Shell	Carbon Steel	ID 93	OD 102.75 in	Shell cover		-		
Channel or bonnet		Carbon Steel		Channel cover		Carbon Steel		
Tubesheet-stationary		Carbon Steel		Tubesheet-floating		-		
Floating head cover		-		Impingement protection		None		
Baffle-cross	Carbon Steel	Type	Single segmen	Cut(%d) 19.8 V	Spacing: c/c		11	in
Baffle-long	-		Seal type			Inlet	13.4062	in
Supportstube			UBend	0	Type			
Bypass seal			Tube-tubesheet joint		Exp. 2 grv			
Expansion joint	-		Type	None				
RhoV2-Inlet nozzle	1099	Bundle entrance		15	Bundle exit		26	lb/(ft-s²)
Gaskets - Shell side	-		Tube Side		Flat Metal Jacket Fibe			
Floating head	-							
Code requirements	ASME Code Sec VIII Div 1			TEMA class		B - chemical service		
Weight/Shell	228571		Filled with water	313977		Bundle	88205.5	lb
Remarks								

HRSG:

Shell ID	in	93
Tube length - actual	ft	15.5
Tube length - required	ft	11.0108
Pressure drop, SS	psi	0.79
Pressure Drop, TS	psi	6.66
Baffle spacing	in	11
Number of baffles		12
Tube passes		1
Tube number		6068
Number of units in series		2
Number of units in parallel		10
Total price	Dollar(US)	13735900
Program mode		Design (Sizing)
Calculation method		Advanced method
Area Ratio (dirty)	-	1.41
Film coef overall, SS	BTU/(h-ft^2-F)	117.86
Film coef overall, TS	BTU/(h-ft^2-F)	33.17
Heat load	BTU/h	1353523000
Recap case fully recoverable		Yes

28.4. Steam Turbine

Cost and Performance Baseline for Fossil Energy Plants Volume 1a: Bituminous Coal (PC) and Natural Gas to Electricity Revision 3 July 6, 2015	
	Steam Turbine of 231 MW cost 36,973,000
	Same source as gas turbine, where a FBM of 2 and $/kW pricing fit the more detailed model extrapolation

Cp	*$ 36,973,000*	*NETL Data*
MW	*231*	
$/MW	*$ 160,056*	
MW	91	
Cp	$ 14,565,121	
FBM	2	
CTBM	$ 29,130,242	

Data from [NETL, 12]

28.5. Condenser

Heat Exchanger Specification Sheet

Company: Group 9										
Location:										
Service of Unit: Steam Condenser			Our Reference:							
Item No.:		Your Reference:								
Date:	Rev No.:	Job No.:								
Size	100 -	240 in	Type	AGL	Hor	Connected in	10	parallel	1	series
Surf/unit(eff.)	304734	ft²	Shells/unit	10		Surf/shell (eff.)	30473.4	ft²		

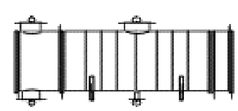
PERFORMANCE OF ONE UNIT

Fluid allocation		Shell Side		Tube Side	
FluidName		Turbine Exit		Cooling Water	
Fluid quantity, Total	lb/h	965794		87333540	
Vapor (In/Out)	lb/h	965794	0	0	0
Liquid	lb/h	0	965794	87333540	87333540
Noncondensable	lb/h	0		0	
Temperature (In/Out)	°F	182.13	100	86	98
Bubble / Dew point	C	178.45 / 178.45	171.9 / 171.9	/	/
Density (Vap / Liq)	lb/ft³	0.019 /	/ 62.132	/ 62.262	/ 62.154
Viscosity	cp	0.0117 /	/ 0.6813	/ 0.7998	/ 0.6961
Molecular wt, Vap		18.01			
Molecular wt, NC					
Specific heat	BTU/(lb-F)	0.478 /	/ 1.0003	/ 1.0008	/ 1.0004
Thermal conductivity	BTU/(ft-h-F)	0.013 /	/ 0.357	/ 0.351	/ 0.356
Latent heat	BTU/lb	990.7	995		
Pressure (abs)	psi	7.2	6.2	65	47.7
Velocity (Mean/Max)	ft/s	104.07 /	262.69	8.4 /	8.41
Pressure drop, allow./calc.	psi	1	6.5	20	17.3
Fouling resistance (min)	ft²-h-F/BTU	0.0005		0.001 0.0012	Ao based
Heat exchanged	1041826690 BTU/h		MTD corrected		75.73 °F
Transfer rate, Service	45.14	Dirty	307.82 Clean	625.7	BTU/(h-ft²-F)

CONSTRUCTION OF ONE SHELL

			Shell Side	Tube Side
Design/vac/test pressure:g		psi	50 / /	80 / /
Design temperature / MDMT		°F	250 /	170 /
Number passes per shell			2	4
Corrosion allowance		in	0.0625	0.0625
Connections	In	in	1 40 / -	1 28 / -
Size/rating	Out		1 6 / -	1 32 / -
Nominal	Intermediate		/ -	/ -

Sketch



Tube No.	8006	OD	0.75	Tks- Avg	0.049 in	Length 240 in	Pitch	0.9375 in
Tubetype	Plain		#/in	Material		Carbon Steel	Tube pattern	90
Shell	Carbon Steel	ID	100	OD	101 in	Shell cover	-	
Channel or bonnet		Carbon Steel				Channel cover	Carbon Steel	
Tubesheet-stationary		Carbon Steel				Tubesheet-floating	-	
Floating head cover		-				Impingement protection	None	
Baffle-cross	Carbon Steel	Type	Single segmen	Cut(%d)	24.9 V	Spacing: c/c	25	in
Baffle-long	Carbon Steel		Seal type				Inlet 33.1562	in
Supportstube			UBend	0	Type			
Bypass seal			Tube-tubesheet joint			Exp. 2 grv		
Expansion joint	-		Type	None				
RhoV2-Inlet nozzle	542	Bundle entrance		690		Bundle exit	2	lb/(ft-s²)
Gaskets - Shell side	-		Tube Side		Flat Metal Jacket Fibe			
Floating head	-							
Code requirements	ASME Code Sec VIII Div 1				TEMA class	B - chemical service		
Weight/Shell	131789		Filled with water		226845.7	Bundle	75529.2	lb
Remarks								

Condenser:

Shell ID	in	100
Tube length - actual	ft	20
Tube length - required	ft	2.9331
Pressure drop, SS	psi	6.5
Pressure Drop, TS	psi	17.3
Baffle spacing	in	25
Number of baffles		6
Tube passes		4
Tube number		8006
Number of units in series		1
Number of units in parallel		10
Total price	Dollar(US)	5392970
Program mode		Design (Sizing)
Calculation method		Advanced method
Area Ratio (dirty)	-	6.82
Film coef overall, SS	BTU/(h-ft^2-F)	1187.16
Film coef overall, TS	BTU/(h-ft^2-F)	1640.27
Heat load	BTU/h	1041827000
Recap case fully recoverable		Yes

28.6. Centrifugal Pumps

Centrifugal Pumps	*From Equipment Costing spreadsheet in Seider et al*									
FBM =	3.3		CE =	600						
Name	Q	H	S	CB	FT	FM	CP	CP	CBM	Check
	(gal/min)	*(ft)*	*(gpm)(ft)^.5*	*$ (CE=567)*	*Table 22.20*	*Table 22.21*	*$ (CE=567)*	*$ (Given CE)*	*$ (Given CE)*	
Pump	1965.1	957.6	60810	22352	8.9	1	198935	**$ 210,513**	**694693**	0

FBM =	3.3		CE =	600					
Name	Q	H	S	CB	FT	FM	CP	CP	CBM
	(gal/min)	*(ft)*	*(gpm)(ft)^.5*	*$ (CE=567)*	*Table 22.20*	*Table 22.21*	*$ (CE=567)*	*$ (Given CE)*	*$ (Given CE)*
O2 Pump (ASU)	897	3581	53678	20372	8.9	2	362623	**$ 383,728**	**1266302**

NGCC **Allam** ***Costing correlations from [19], Equipment Design***

28.7. Electric Motors

NGCC:

Motor for Pump			
	Equations from Ch.16 Seider et al		
	PB	549.54	
	nm	0.928815493	
	Pc	591.6567972	
	CB	36551.07153	
	Ft	1.8	
	Cp	**$ 65,792**	
	FBM	3.21	
	CBM	$ 211,192.09	

Allam:

Motor for Pump		
	Source: Seider et al	
	PB	1057
	nm	0.933881214
	Pc	1131.835596
	CB	54663.91618
	Ft	1.8
	Cp	**$ 98,395**
	FBM	3.21
	CTBM	$ 315,848

28.8. Cansolv Amine Scrubbing Unit

Exhibit 5-3. Cansolv CO_2 capture process typical flow diagram for NGCC

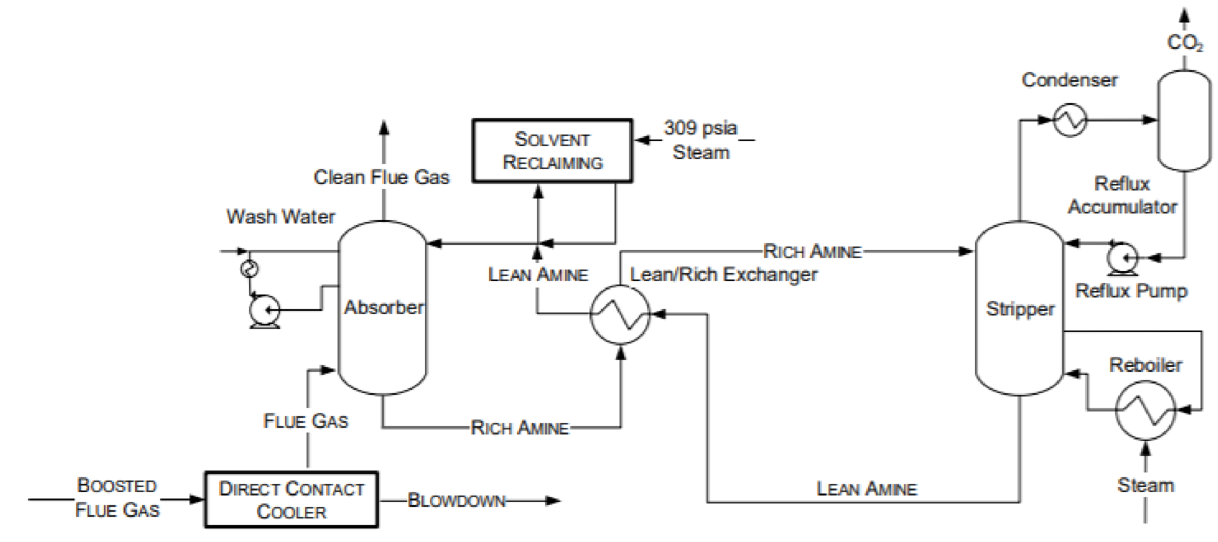


Image (above) and costing (below) from [13]

	Doe/NETL COST AND PERFORMANCE BASELINE FOR FOSSIL ENERGY PLANTS VOLUME 1: BITUMINOUS COAL AND NATURAL GAS TO ELECTRICITY	
	Utilizes Cansolv CO2 removal system at a total plant cost of $618,768,000 to produce 11,219 lbmol/hr of CO2 at 99% purity	
CTPI	*$ 618,768,000*	*NETL Data*
CTBM	*$ 423,910,704*	*discount back to CTBM*
lbmol/hr CO2	*11219*	
$/lbmol CO2	*$ 37,785*	
FBM	*1*	*installed cost given*
lbmol/hr CO2	7062	NGCC w/CDR
CTBM	**$ 266,838,167**	

Cansolv unit in [13] requires 10.6 MW for 305,000 lbmol/hr of flue gas at a CO2 concentration of 4.1%. Stream 107 in NGCC is 231,000 lbmol/hr and is 3.4% CO2. Adjusting for total flow rate proportionally and the standard Sherwood plot which predicts the efficiency varies linearly with concentration, the required power = 10.6*(231,000/305,000)*(4.1/3.4) = 9.7 MW.

28.9. Coolers

NGCC:

FBM =	3.17		CE =	600								
Name	Heat Exchanger Design	Surface Area	CB	a	b	FM	Pressure	Fp	FL	Cp	Cp	CBM
		ft^2	$ (CE=567)	Table 22.25	Table 22.25		psig		See below	$ (CE=567)	$(Given CE)	$ (Given CE)
Pipeline CO2 Cooler	Fixed Head	953	16789	0	0	1	1726	1.797423	1	30177	$ 31,933	101228

Allam:

All coolers treated as black-box shell and tube HXs									
	Q(Btu/hr)	Thin	Thout	Tcin	Tcout	LMTD (F)	UA (Btu/hr-F)	A(ft^2)	
Cooler1	3.54E+08	188	92	90	120	18.7	1.89E+07	126,094	*Out of textbook range, use ACCE to justify*
Cooler2	5.33E+06	100	80	71.24	87.8	10.4	5.13E+05	3,422	Equip. Design Spreadsheet
Cooler3	3.97E+07	100	93	90	95	3.9	1.01E+07	67,599	*Out of textbook range, use ACCE to justify*
ASU/Allam-HX	1.14E+08	234	190	146	170	53.4	2.14E+06	14,238	Equip. Design Spreadsheet

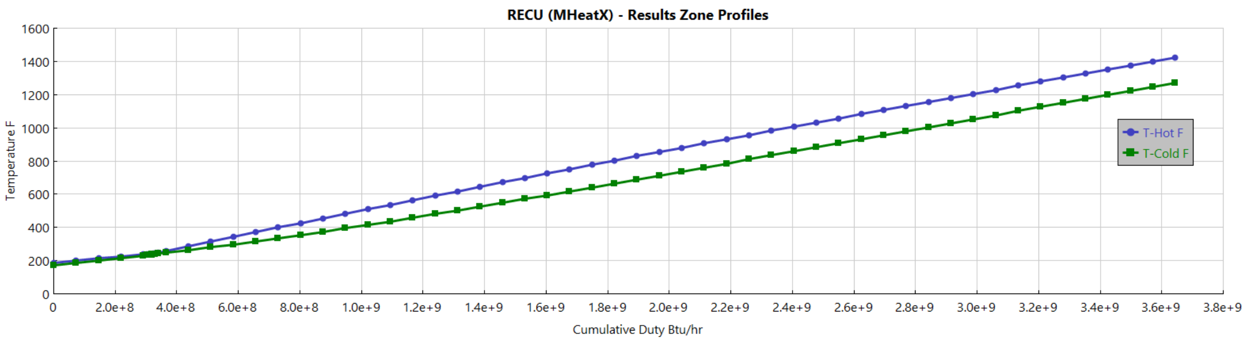
ıd Tube Heat Exchangers			CE =	600										
FBM =	3.17	*for cooler2, cooler3, ASU/Allam-HX*												
FBM =	2.2	*for cooler1*												
Name		Area	CB	a	b	FM	Pressure	Fp	FL	Cp	**Cp**	Cp	CBM	CBM
		ft^2	$ (CE=567)	Table 22.25	Table 22.25	carbon steel	psig			$ (CE=567)	**$(Given CE)**	ACCE	$ (Given CE)	ACCE
Cooler2	Fixed Head	3422	34177	0	0	1	1726	1.7974229	1	61430	**$ 65,005**	--	206066	--
ASU/Allam-HX	Fixed Head	14238	110460	0	0	1	4341	4.9652078	1	548459	**$ 580,380**	--	1839804	--
Cooler3	Fixed Head	67599	629224	0	0	1	1726	1.7974229	1	1130981	**$ 1,196,806**	$ 1,868,900	3793874	4019815
														good to use
Cooler1	Fixed Head	126094	1443630	0	0	1	400	1.0795	1	1558399	**$ 1,649,099**	$ 2,124,500	3628019	3500795
Fixed head:														need to adj

From [19], except where ACCE is noted

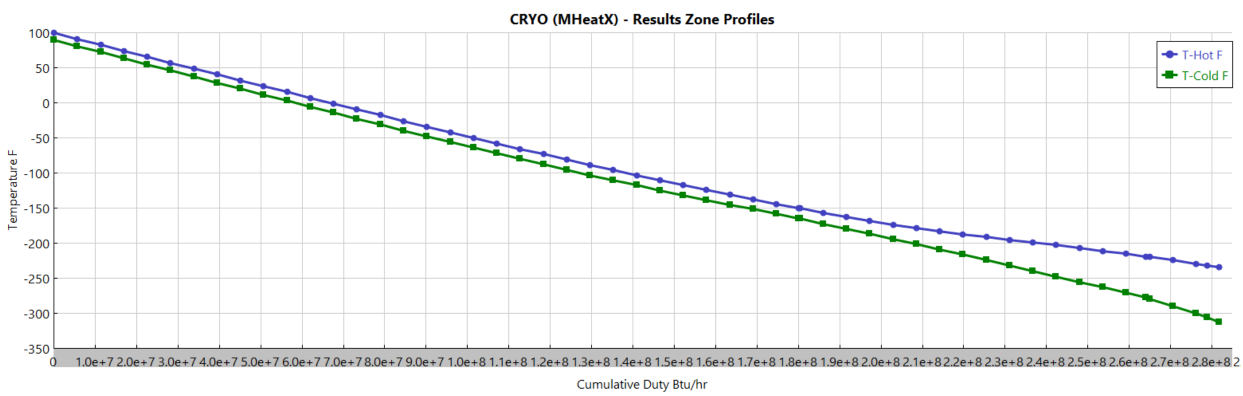
28.10. Allam Cycle HX's

0.263	$/UA (specified by project author, Adam Brostow)			
HX	UA	Cp	Fbm	CBM
Cryogenic HX	1.73E+07	**$ 4,549,900**	3	$13,649,700
Recuperator	6.92E+07	**$ 18,199,600**	3	$54,598,800
Reboil/Condenser	4.76E+06	**$ 1,251,880**	3	$ 3,755,640

Heat Curve for Recuperator



Heat Curve for Cryogenic HX

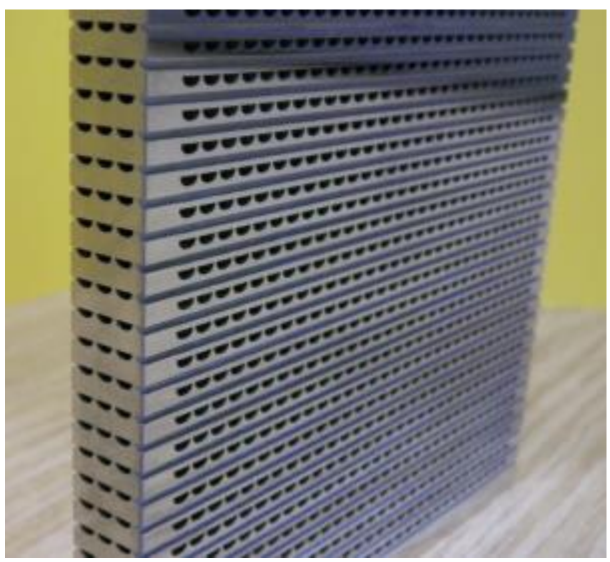


Images of a printed circuit heat exchanger (PCHE) from Heatric [23].

“Heatric’s Printed Circuit Heat Exchangers (PCHEs) are manufactured using a specialised solid-state joining process known as ‘diffusion-bonding’. This process creates a heat exchanger core with no joints, welds, or points of failure. The resulting unit combines exceptional strength and integrity with high efficiency and performance” [23].

Outside of a PCHE [23]:

Inside cross-section of cross-flow PCHE [23]:



28.11. Expander

C_p=600P^0.81 for carbon steel expander in range of 20-50,000 hp				
	Source: Ch.16 Seider et al			
Let FM = 2 as is done for stainless steel compressors				
CE	600			
hp	1956			
Fm	2			
Cp (CE=567)	$ 525,559			
Cp(given CE)	**$ 556,148**			
FBM	3.21			
CTBM	$ 1,785,234			

From [19]

28.12. Packed Columns

Aspen Col. Internals:

Start Stage	End Stage	Mode	Internal Type	Tray/Packing Type	Tray Details		Packing Details			Tray Spacing/Section Packed Height		Diameter	
					Number of Passes	Number of Downcomers	Vendor	Material	Dimension				
1	38	Interactive sizing	Packed	FLEXIPAC			KOCH	METAL	4Y	380	in	17.0704	ft

Start Stage	End Stage	Mode	Internal Type	Tray/Packing Type	Tray Details		Packing Details			Tray Spacing/Section Packed Height		Diameter	
					Number of Passes	Number of Downcomers	Vendor	Material	Dimension				
2	14	Interactive sizing	Packed	FLEXIPAC			KOCH	METAL	4Y	130	in	13.6545	ft

Costing from [19]

FBM =	4.16		CE =	600																	
Name	Di	L	Pressure	Pd	E	Stress (S)	tp	Wind/Earthquake?	tw	taverage	Corrosion tc	ts	tsrounded	tsrounded	Density	Weight	Cv	Cpl	Fm	Cp	CP
	ft	ft	psig	psig		psi (see below)	ft	Include=Y	ft	ft	inch	inch	inch	ft	lb/ft^3	lb	$ (CE=567)	$ (CE=567)	Table 22.26	$(CE=567)	$ (Given CE)
HPC	14	17	70	92	1	15000	0.04330	Y	0.00033	0.04347	0.125	0.6466	0.7500	0.0625	170	13237	62863	17577	3	206166	$ **218,165**
LPC	17	41	13	19	1	15000	0.01101	Y	0.00158	0.01180	0.125	0.2666	0.5000	0.0417	170	20706	82142	40257	3	286683	$ **303,369**
			Note: see text for vacuum vessels																		

Vp	Packing Classification	Cpk structured	Cpk dumped	A	Cdr	Cp (only packing)	Cp (only packing)	Cbm
ft^3	(dumped or structured)	$ (CE=567)	Table 22.27 $ (CE=567)	ft^2	$ (CE=567)	$ (CE=567)	$ (Given CE)	$ (Given CE)
1693	Structured	285		153.94	21551	504147	$ **533,489**	3126880
7263	Structured	285		226.98	31777	2101835	$ **2,224,164**	10514537

Images for supplemental column internals from Koch-Glitsch [24]

Typical bed limiter at the bottom of the column to avoid packing displacement [24]:

Typical feed distributer on top of packing [24]:

28.13. Pressure Vessels

separator sizing	two in parallel
V, ft/√sec	650
rho-l	60.2
rho-g	2.09
Uflood	5.28
U	4.49
Di	14.3
H	43

Coldbox	
Coldboxes are generally filled with Perlite to maintain insulation	
The cost, for purposes of this project, are calculated as material to co	
diameter LPC	17
height of LPC + HPC	58
width coldbox (ft)	19
equivalent diameter (=4w/pi)	*24*
height coldbox (ft)	*60*
Pressure Vessels	

Di	L	Pressure	Pd	E	S	tp	nd/Earthqua	tw	taverage	Corrosion tc	ts	tsrounded	tsrounded	Density	Weight	Cv	Cpl	Fm	Cp	CP	Cbm
ft	*ft*	*psig*	*psig*		*psi (see below*	*ft*	*Include=Y*	*ft*	*ft*	*inch*	*inch*	*inch*	*ft*	*lb/ft^3*	*lb*	*$ (CE=567)*	*$ (CE=567)*	*Table 22.26*	*$(CE=567)*	*$ (Given CE)*	*$ (Given CE)*
14.3	43	231	281	1	13750	0.14810	Y	0.00223	0.14921	1.125	2.91555	3.00000	0.2500	491	305472	493074	41829	1	534903	**$ 566,035**	**2354707**
24	60	0.1	0	1	11200	0.00024	Y	0.00310	0.00179	0.125	0.14653	0.50000	0.0417	490	123342	251593	78107	1	329699	**$ 348,888**	**1119930**

Costing for pressure vessels from guidelines in [19].

Image from Sulzer [25] of coldox reaching 60m:

1 Up to 60 m high cold boxes maintain the cryogenic temperatures in air separation units.
Sulzer installed these units at the Sichuan Air Separation Group in China.

28.14. Allam Cycle Pumps

ACCE Used for barrel pumps

Parameter	Value	Units
Item type	CENTRIF	
Number of identical items	1	
EQUIPMENT DESIGN DATA		
Casing material	CS	
Design temperature	145.000	DEG F
Operating temperature	145.000	DEG F
Design gauge pressure	4341.000	PSIG
Fluid head	10400.00	FEET
ASA rating	2500	CLASS
Brake horsepower	23041.85	HP
Driver power	13378.00	HP
Speed	1800.000	RPM
Driver type	GAS ENGINE	
Pump efficiency	85.000	PERCENT
Seal type	SNGL	
PROCESS DESIGN DATA		
Liquid flow rate	7454.000	GPM

WEIGHT DATA		
Pump	89600	LBS
Gas engine	121400	LBS
Base plate	18600	LBS
Fittings and miscellaneous	15800	LBS
Total weight	245400	LBS
VENDOR COST DATA		
Gas engine cost	568000	DOLLARS
Material cost	129556	DOLLARS
Shop labor cost	574337	DOLLARS
Shop overhead cost	585823	DOLLARS
Office overhead cost	315812	DOLLARS
Profit	347773	DOLLARS
Total cost	2521301	DOLLARS
Cost per unit weight	10.274	USD/LBS
Cost per unit liquid flow rate	338.248	USD/GPM
Cost per unit power	188.466	USD/HP

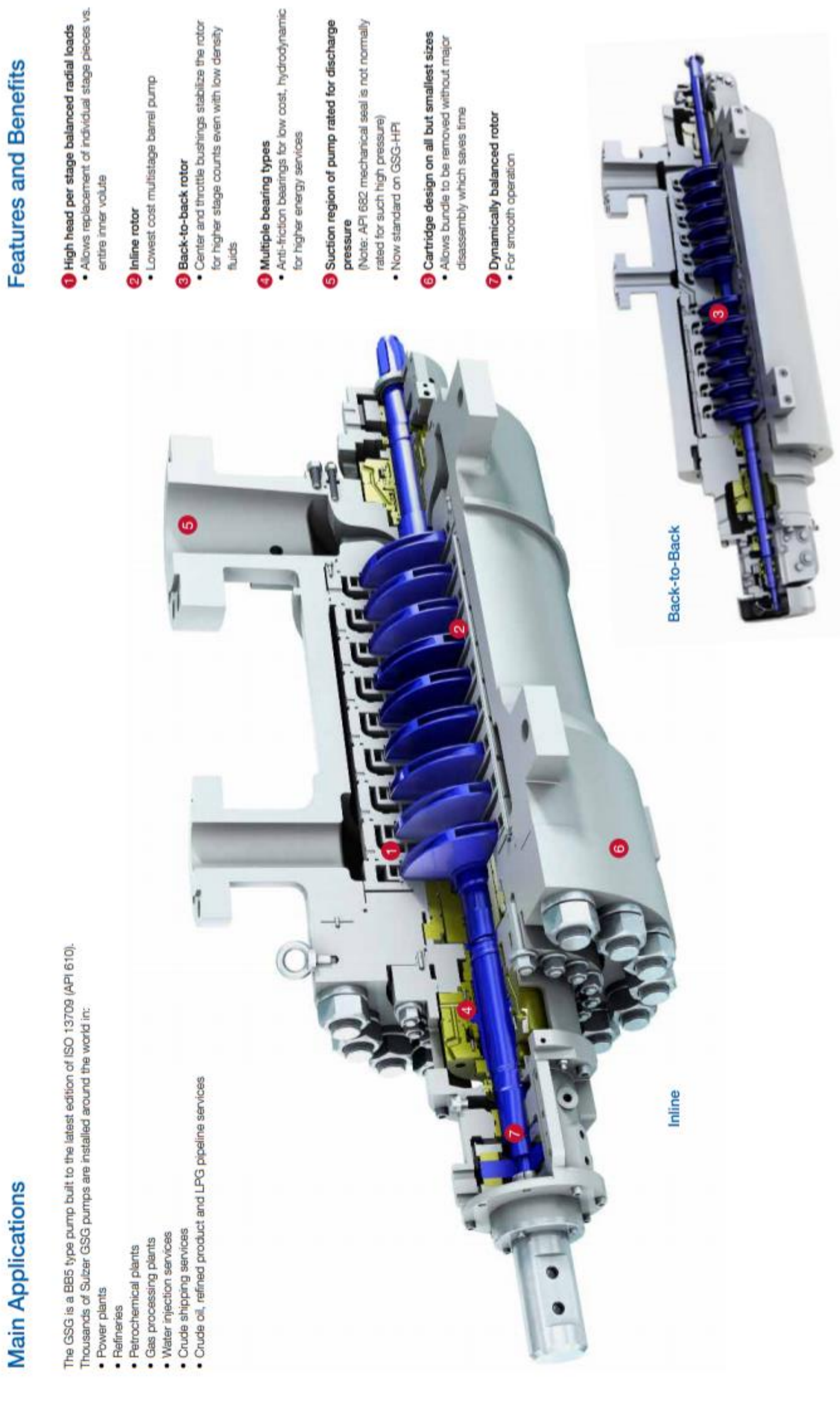
Parameter	Value	Units
Item type	CENTRIF	
Number of identical items	1	
EQUIPMENT DESIGN DATA		
Casing material	CS	
Design temperature	145.000	DEG F
Operating temperature	145.000	DEG F
Design gauge pressure	4341.000	PSIG
Fluid head	8961.000	FEET
ASA rating	2500	CLASS
Brake horsepower	22125.62	HP
Driver power	14881.00	HP
Speed	1800.000	RPM
Driver type	GAS ENGINE	
Pump efficiency	85.000	PERCENT
Seal type	SNGL	
PROCESS DESIGN DATA		
Liquid flow rate	8307.000	GPM

WEIGHT DATA		
Pump	67600	LBS
Gas engine	133800	LBS
Base plate	14000	LBS
Fittings and miscellaneous	11900	LBS
Total weight	227300	LBS
VENDOR COST DATA		
Gas engine cost	626000	DOLLARS
Material cost	97984	DOLLARS
Shop labor cost	433329	DOLLARS
Shop overhead cost	441995	DOLLARS
Office overhead cost	271883	DOLLARS
Profit	299410	DOLLARS
Total cost	2170601	DOLLARS
Cost per unit weight	9.5495	USD/LBS
Cost per unit liquid flow rate	261.298	USD/GPM
Cost per unit power	145.864	USD/HP

Source: Aspen Capital Cost Estimator (ACCE) v11.1								
	Q (gpm)	H (ft)	hp	total cost (ACCE)	turbine cost	Cp	FBM	CTBM
O2/CO2 Pump	7454	10400	13378	$ 2,521,301	$ 568,000	**$ 1,953,301**	2	$ 3,906,602
CO2 Pump	8307	8961	14881	$ 2,170,601	$ 626,000	**$ 1,544,601**	2	$ 3,089,202

Subtract engine cost since already included in turbine cost.

Diffuser style barrel pump from Sulzer [26] which can produce pressure heads to 10,000 ft:



28.15. Pipelines and Accessory Electric Plant

Cost and Performance Baseline for Fossil Energy Plants Volume 1a: Bituminous Coal (PC) and Natural Gas to Electricity Revision 3 July 6, 2015 DOE/NETL-2015/1723

ACCESSORY ELECTRIC PLANT

Includes generator equip, station servic equp, coduit and cable tray, wire, prtective equip, power transformers, foundations

bare erected cost of $37,828,000 for 630 net MW = $60,044/MW

Net MW	300
CTBM	**$18,013,200**

NATURAL GAS PIPELINE

NETL calc bare erected cost of $18,929,000 for 2456 acfm natural gas

acfm	1600
CTBM	**$12,331,596**

Equipment No.	Description	Type	Design Condition	Operating Qty.	Spares
1	Gas Pipeline	Underground, coated carbon steel, wrapped cathodic protection	70 m^3/min @ 3.1 MPa (2,456 acfm @ 450 psia) 39 cm (16 in) standard wall pipe	16 km (10 mi)	0

CO2 PIPELINE

Techno-Economic Models for Carbon Dioxide Compression, Transport, and Storage & Correlations for Estimating Carbon Dioxide Density and Viscosity

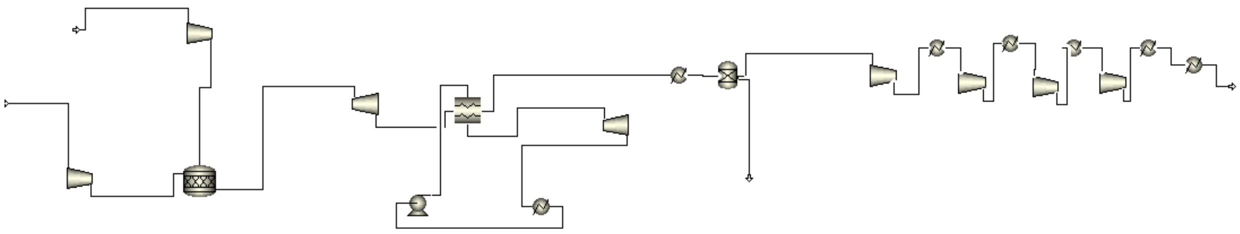
assume 10 mi (16km) pipeline investment is needed to reach larger pipeline network

$/km (capital inv)	$ 280,000
km	16
CTPI	$ 4,480,000
CTBM	**$ 3,069,195**

NG Pipeline & Accessory Electric Plant [12]

CO2 Pipeline [21]

28.18. NGCC Aspen Input



```
DYNAMICS
   DYNAMICS RESULTS=ON
IN-UNITS ENG SHORT-LENGTH=in
DEF-STREAMS CONVEN ALL
MODEL-OPTION
DATABANKS 'APV110 PURE37' / 'APV110 AQUEOUS' / 'APV110 SOLIDS' &
       / 'APV110 INORGANIC' / 'APESV110 AP-EOS' /  &
      'NISTV110 NIST-TRC' / NOASPENPCD
PROP-SOURCES 'APV110 PURE37' / 'APV110 AQUEOUS' /  &
      'APV110 SOLIDS' / 'APV110 INORGANIC' / 'APESV110 AP-EOS' &
       / 'NISTV110 NIST-TRC'
COMPONENTS
   OXYGEN O2 /
   NITROGEN N2 /
   METHANE CH4 /
   WATER H2O /
   CARBO-01 CO2
SOLVE
   RUN-MODE MODE=SIM
FLOWSHEET
   BLOCK COMBUST IN=102 104 OUT=105
   BLOCK GAS-TURB IN=105 OUT=106
   BLOCK PUMP IN=110 OUT=111
   BLOCK COND IN=109 OUT=110
   BLOCK STM-TURB IN=108 OUT=109
   BLOCK AIR-COMP IN=101 OUT=102
```

```
    BLOCK HRSG IN=106 111 OUT=107 108
    BLOCK NG-COMP IN=103 OUT=104
    BLOCK AMINE2 IN=107B OUT=113 112
    BLOCK CO2COMP1 IN=113 OUT=113B
    BLOCK CW1 IN=113B OUT=113C
    BLOCK CO2COMP2 IN=113C OUT=113D
    BLOCK CO2COMP3 IN=113E OUT=113F
    BLOCK CO2COMP4 IN=113G OUT=113H
    BLOCK CW2 IN=113D OUT=113E
    BLOCK CW3 IN=113F OUT=113G
    BLOCK CW4 IN=113H OUT=114
    BLOCK REFRIG IN=114 OUT=115
    BLOCK AMINE1 IN=107 OUT=107B
PROPERTIES PENG-ROB
PROP-DATA PRKBV-1
    IN-UNITS MET PRESSURE=bar TEMPERATURE=C DELTA-T=C PDROP=bar  &
        INVERSE-PRES='1/bar' SHORT-LENGTH=mm
    PROP-LIST PRKBV
    BPVAL OXYGEN NITROGEN -.0119000000 0.0 0.0 -273.1500000  &
        726.8500000
    BPVAL NITROGEN OXYGEN -.0119000000 0.0 0.0 -273.1500000  &
        726.8500000
    BPVAL NITROGEN METHANE .0311000000 0.0 0.0 -273.1500000  &
        726.8500000
    BPVAL METHANE NITROGEN .0311000000 0.0 0.0 -273.1500000  &
        726.8500000
    BPVAL NITROGEN CARBO-01 -.0170000000 0.0 0.0 -273.1500000  &
        726.8500000
    BPVAL CARBO-01 NITROGEN -.0170000000 0.0 0.0 -273.1500000  &
        726.8500000
    BPVAL METHANE CARBO-01 .0919000000 0.0 0.0 -273.1500000  &
        726.8500000
    BPVAL CARBO-01 METHANE .0919000000 0.0 0.0 -273.1500000  &
        726.8500000
    BPVAL WATER CARBO-01 .1200000000 0.0 0.0 -273.1500000  &
```

```
        726.8500000
    BPVAL CARBO-01 WATER .1200000000 0.0 0.0 -273.1500000  &
        726.8500000
STREAM 101
    SUBSTREAM MIXED TEMP=70. PRES=0. <psig>  &
        MASS-FLOW=3216.583 <tons/hr>
    MOLE-FRAC OXYGEN 0.21 / NITROGEN 0.79 / METHANE 0. /  &
        WATER 0. / CARBO-01 0.
STREAM 103
    SUBSTREAM MIXED TEMP=100. PRES=465.  &
        MASS-FLOW=62.938 <tons/hr>
    MASS-FRAC OXYGEN 0. / NITROGEN 0. / METHANE 1. / WATER  &
        0. / CARBO-01 0.
STREAM 110
    SUBSTREAM MIXED TEMP=100. PRES=6. MOLE-FLOW=53609.721
    MASS-FRAC WATER 1.
STREAM 111
    SUBSTREAM MIXED TEMP=174.65 PRES=25. <psig>  &
        MASS-FLOW=1463.106 <tons/hr>
    MOLE-FRAC OXYGEN 0. / NITROGEN 0. / METHANE 0. / WATER  &
        1. / CARBO-01 0.
BLOCK AMINE2 SEP
    PARAM
    FRAC STREAM=113 SUBSTREAM=MIXED COMPS=NITROGEN CARBO-01  &
        FRACS=0.00045 0.9
BLOCK AMINE1 HEATER
    PARAM TEMP=86. PRES=0. DPPARMOPT=NO
BLOCK COND HEATER
    PARAM TEMP=100. PRES=0. NPHASE=2 DPPARMOPT=NO
    BLOCK-OPTION FREE-WATER=NO
BLOCK CW1 HEATER
    PARAM TEMP=100. PRES=68.6 DPPARMOPT=NO
BLOCK CW2 HEATER
    PARAM TEMP=100. PRES=199.45 DPPARMOPT=NO
BLOCK CW3 HEATER
```

```
   PARAM TEMP=100. PRES=589.35 DPPARMOPT=NO
BLOCK CW4 HEATER
   PARAM TEMP=100. PRES=1731. <psig> DPPARMOPT=NO
BLOCK REFRIG HEATER
   PARAM TEMP=80. PRES=1726. <psig> DPPARMOPT=NO
BLOCK HRSG MHEATX
   HOT-SIDE IN=106 OUT=107 TEMP=400. FREE-WATER=NO  &
      DPPARMOPT=NO
   COLD-SIDE IN=111 OUT=108 FREE-WATER=NO DPPARMOPT=NO
   PARAM NPOINT=50 ADAPTIVE-GRI=YES
   HCURVE 106 106
   HCURVE 111 111
BLOCK COMBUST RSTOIC
   PARAM PRES=0. DUTY=0. HEAT-OF-REAC=YES
   STOIC 1 MIXED METHANE -1. / OXYGEN -2. / CARBO-01 1. /  &
      WATER 2.
   CONV 1 MIXED METHANE 1.
   HEAT-RXN REACNO=1 CID=METHANE
BLOCK PUMP
   PARAM PRES=400. <psig> EFF=0.85
BLOCK AIR-COMP COMPR
   PARAM TYPE=ISENTROPIC PRES=600. SEFF=0.85 SB-MAXIT=30  &
      SB-TOL=0.0001
BLOCK CO2COMP1 COMPR
   PARAM TYPE=ASME-POLYTROP PRATIO=2.98 PEFF=0.85 SB-MAXIT=30  &
      SB-TOL=0.0001
BLOCK CO2COMP2 COMPR
   PARAM TYPE=ASME-POLYTROP PRATIO=2.98 PEFF=0.85 SB-MAXIT=30  &
      SB-TOL=0.0001
BLOCK CO2COMP3 COMPR
   PARAM TYPE=ASME-POLYTROP PRATIO=2.98 PEFF=0.85 SB-MAXIT=30  &
      SB-TOL=0.0001
BLOCK CO2COMP4 COMPR
   PARAM TYPE=ASME-POLYTROP PRES=1736. <psig> PEFF=0.85  &
      SB-MAXIT=30 SB-TOL=0.0001
```

```
BLOCK GAS-TURB COMPR
   PARAM TYPE=ISENTROPIC PRES=10. <psig> SEFF=0.85 SB-MAXIT=30  &
      SB-TOL=0.0001 MODEL-TYPE=TURBINE
BLOCK NG-COMP COMPR
   PARAM TYPE=ASME-POLYTROP PRES=600. PEFF=0.85 SB-MAXIT=30  &
      SB-TOL=0.0001
BLOCK STM-TURB COMPR
   PARAM TYPE=ISENTROPIC PRES=-7.5 <psig> SEFF=0.85 NPHASE=2  &
      SB-MAXIT=30 SB-TOL=0.0001 MODEL-TYPE=TURBINE
   BLOCK-OPTION FREE-WATER=NO
EO-CONV-OPTI
STREAM-REPOR MOLEFLOW
PROPERTY-REP PCES
```

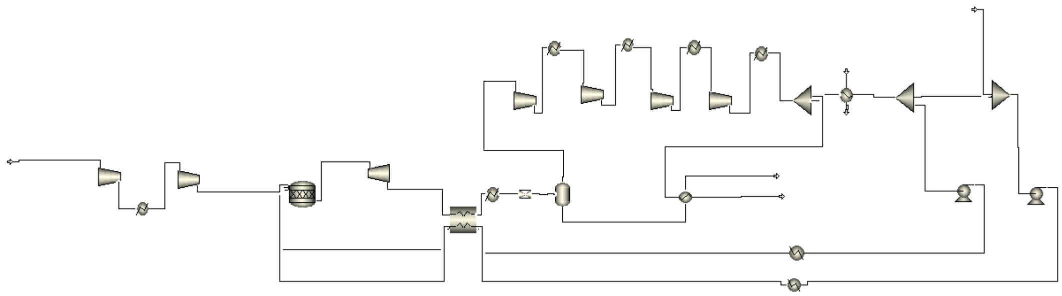
28.19. NGCC Full Aspen Stream Report

All stream numbers match number in report. Streams with letter (B, C, D, ...) indicate an intermediate stream for compressor intercooling.

	Units	101	102	103	104	105	106	107	107B	108	109	110
Description												
From			AIR-COMP		NG-COMP	COMBUST	GAS-TURB	HRSG	AMINE1	HRSG	STM-TURE	COND
To		AIR-COMF	COMBUST	NG-COMP	COMBUST	GAS-TURB	HRSG	AMINE1	AMINE2	STM-TURE	COND	PUMP
Stream Class		CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN
Maximum Relative Error												
Cost Flow	$/hr											
MIXED Substream												
Phase		Vapor Pha	Vapor Pha	Vapor Pha	Vapor Pha	Vapor Pha	Vapor Pha	Vapor Phase		Vapor Phase		Liquid Pha
Temperature	F	70	1173.192	100	140.7247	2490.786	1173.642	400	86	854.0113	182.1302	100
Pressure	psig	-1.78E-15	585.3041	450.3041	585.3041	585.3041	10	10	10	400	-7.5	-7.5
Molar Vapor Fraction		1	1	1	1	1	1	1	0.951932	1	0.98146	0
Molar Liquid Fraction		0	0	0	0	0	0	0	0.048068	0	0.01854	1
Molar Solid Fraction		0	0	0	0	0	0	0	0	0	0	0
Mass Vapor Fraction		1	1	1	1	1	1	1	0.969525	1	0.98146	0
Mass Liquid Fraction		0	0	0	0	0	0	0	0.030475	0	0.01854	1
Mass Solid Fraction		0	0	0	0	0	0	0	0	0	0	0
Molar Enthalpy	Btu/lbmol	-52.3656	8049.631	-32073.5	-31747.9	6696.85	-4566.52	-10499.9	-13705	-97685.5	-103476	-123259
Mass Enthalpy	Btu/lb	-1.81507	279.0128	-1999.25	-1978.95	235.6797	-160.708	-369.52	-482.316	-5422.37	-5743.77	-6841.93
Molar Entropy	Btu/lbmol-R	0.923542	1.705859	-26.0476	-25.9634	6.763782	8.084379	3.187863	-1.74373	-9.89503	-8.30296	-39.303
Mass Entropy	Btu/lb-R	0.032011	0.059128	-1.62364	-1.61839	0.238035	0.284511	0.112189	-0.06137	-0.54926	-0.46088	-2.18165
Molar Density	lbmol/cuft	0.002587	0.033841	0.082173	0.098645	0.018817	0.001408	0.002677	0.004435	0.030417	0.00107	3.401326
Mass Density	lb/cuft	0.074635	0.976327	1.318289	1.582542	0.534697	0.040018	0.076055	0.126031	0.547976	0.01927	61.27584
Enthalpy Flow	Btu/hr	-1.2E+07	1.79E+09	-2.5E+08	-2.5E+08	1.55E+09	-1.1E+09	-2.4E+09	-3.2E+09	-5.2E+09	-5.5E+09	-6.6E+09
Average MW		28.8504	28.8504	16.04276	16.04276	28.41504	28.41504	28.41504	28.41504	18.01528	18.01528	18.01528
Mole Flows	lbmol/hr	222983.6	222983.6	7846.281	7846.281	230829.9	230829.9	230829.9	230829.9	53609.72	53609.72	53609.72
OXYGEN	lbmol/hr	46826.56	46826.56	0	0	31134	31134	31134	31134	0	0	0
NITROGEN	lbmol/hr	176157.1	176157.1	0	0	176157.1	176157.1	176157.1	176157.1	0	0	0
METHANE	lbmol/hr	0	0	7846.281	7846.281	0	0	0	0	0	0	0
WATER	lbmol/hr	0	0	0	0	15692.56	15692.56	15692.56	15692.56	53609.72	53609.72	53609.72
CARBO-01	lbmol/hr	0	0	0	0	7846.281	7846.281	7846.281	7846.281	0	0	0
Mole Fractions												
OXYGEN		0.21	0.21	0	0	0.134879	0.134879	0.134879	0.134879	0	0	0
NITROGEN		0.79	0.79	0	0	0.763147	0.763147	0.763147	0.763147	0	0	0
METHANE		0	0	1	1	0	0	0	0	0	0	0
WATER		0	0	0	0	0.067983	0.067983	0.067983	0.067983	1	1	1
CARBO-01		0	0	0	0	0.033992	0.033992	0.033992	0.033992	0	0	0
Mass Flows	tons/hr	3216.583	3216.583	62.938	62.938	3279.521	3279.521	3279.521	3279.521	482.8971	482.8971	482.8971
OXYGEN	tons/hr	749.1969	749.1969	0	0	498.1253	498.1253	498.1253	498.1253	0	0	0
NITROGEN	tons/hr	2467.386	2467.386	0	0	2467.386	2467.386	2467.386	2467.386	0	0	0
METHANE	tons/hr	0	0	62.938	62.938	0	0	0	0	0	0	0
WATER	tons/hr	0	0	0	0	141.3529	141.3529	141.3529	141.3529	482.8971	482.8971	482.8971
CARBO-01	tons/hr	0	0	0	0	172.6566	172.6566	172.6566	172.6566	0	0	0
Mass Fractions												
OXYGEN		0.232917	0.232917	0	0	0.15189	0.15189	0.15189	0.15189	0	0	0
NITROGEN		0.767083	0.767083	0	0	0.752362	0.752362	0.752362	0.752362	0	0	0
METHANE		0	0	1	1	0	0	0	0	0	0	0
WATER		0	0	0	0	0.043102	0.043102	0.043102	0.043102	1	1	1
CARBO-01		0	0	0	0	0.052647	0.052647	0.052647	0.052647	0	0	0
Volume Flow	cuft/min	1436586	109819.2	1591.406	1325.673	204447.2	2731736	1437342	867385.9	29374.58	835316.8	262.6903
Vapor Phase												
Molar Enthalpy	Btu/lbmol	-52.3656	8049.632	-32073.5	-31747.9	6696.85	-4566.52	-10499.9	-8159.42	-97685.5	-103132	
Mass Enthalpy	Btu/lb	-1.81507	279.0129	-1999.25	-1978.95	235.6797	-160.708	-369.52	-281.941	-5422.37	-5724.71	
Molar Entropy	Btu/lbmol-R	0.923542	1.705859	-26.0476	-25.9634	6.763782	8.084379	3.187863	0.177719	-9.89503	-7.76787	
Mass Entropy	Btu/lb-R	0.032011	0.059128	-1.62364	-1.61839	0.238035	0.284511	0.112189	0.006141	-0.54926	-0.43118	
Molar Density	lbmol/cuft	0.002587	0.033841	0.082173	0.098645	0.018817	0.001408	0.002677	0.004222	0.030417	0.00105	
Mass Density	lb/cuft	0.074635	0.976327	1.318289	1.582542	0.534697	0.040018	0.076055	0.122198	0.547976	0.018913	
Enthalpy Flow	Btu/hr	-1.2E+07	1.79E+09	-2.5E+08	-2.5E+08	1.55E+09	-1.1E+09	-2.4E+09	-1.8E+09	-5.2E+09	-5.4E+09	
Average MW		28.8504	28.8504	16.04276	16.04276	28.41504	28.41504	28.41504	28.94018	18.01528	18.01528	
Mole Flows	lbmol/hr	222983.6	222983.6	7846.281	7846.281	230829.9	230829.9	230829.9	219734.5	53609.72	52615.8	
Mass Flows	tons/hr	3216.583	3216.583	62.938	62.938	3279.521	3279.521	3279.521	3179.577	482.8971	473.9442	
Volume Flow	cuft/hr	86195184	6589154	95484.37	79540.39	12266831	1.64E+08	86240518	52039919	1762475	50118702	
Liquid Phase												
Molar Enthalpy	Btu/lbmol								-123531		-121655	-123259
Mass Enthalpy	Btu/lb								-6856.99		-6752.91	-6841.93
Molar Entropy	Btu/lbmol-R								-39.7963		-36.6294	-39.303
Mass Entropy	Btu/lb-R								-2.20903		-2.03324	-2.18165
Molar Density	lbmol/cuft								3.427574		3.242341	3.401326
Mass Density	lb/cuft								61.74881		58.41168	61.27584
Enthalpy Flow	Btu/hr								-1.4E+09		-1.2E+08	-6.6E+09
Mole Flows	lbmol/hr								11095.43		993.9192	53609.72
Mass Flows	tons/hr								99.94385		8.952867	482.8971
Volume Flow	cuft/hr								3237.11		306.5437	15761.42

	Units	111	112	113	113B	113C	113D	113E	113F	113G	113H	114	115
Description													
From		PUMP	AMINE2	AMINE2	CO2COMF	CW1	CO2COMF	CW2	CO2COMF	CW3	CO2COMP4	CW4	REFRIG
To		HRSG		CO2COMF	CW1	CO2COMF	CW2	CO2COMF	CW3	CO2COMF	CW4	REFRIG	
Stream Class		CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN
Maximum Relative Error													
Cost Flow	$/hr												
MIXED Substream													
Phase		Liquid Phase		Vapor Pha	Vapor Pha	Vapor Pha	Vapor Pha	Vapor Pha	Vapor Pha	Vapor Pha	Vapor Phase	Vapor Pha	Liquid Pha
Temperature	F	100.2984	86	86	256.7624	100	275.2536	100	280.4338	100	286.56825	100	80
Pressure	psig	400	10	10	58.89798	53.90405	189.7321	184.7541	579.6651	574.6541	1736	1731	1726
Molar Vapor Fraction		0	0.949711	1	1	1	1	1	1	1	1	1	0
Molar Liquid Fraction		1	0.050289	0	0	0	0	0	0	0	0	0	1
Molar Solid Fraction		0	0	0	0	0	0	0	0	0	0	0	0
Mass Vapor Fraction		0	0.967554	1	1	1	1	1	1	1	1	1	0
Mass Liquid Fraction		1	0.032446	0	0	0	0	0	0	0	0	0	1
Mass Solid Fraction		0	0	0	0	0	0	0	0	0	0	0	0
Molar Enthalpy	Btu/lbmol	-123233.2	-8817.07	-167250	-165663	-167174	-165570	-167331	-165798	-167878	-166562.99	-171181	-171876
Mass Enthalpy	Btu/lb	-6840.482	-315.765	-3815.68	-3779.47	-3813.94	-3777.37	-3817.53	-3782.57	-3830.02	-3800.0121	-3905.36	-3921.23
Molar Entropy	Btu/lbmol-R	-39.30246	-2.07143	-0.11641	0.261126	-1.97734	-1.60535	-4.29111	-3.93664	-7.15123	-6.8503289	-14.2102	-15.4734
Mass Entropy	Btu/lb-R	-2.181618	-0.07418	-0.00266	0.005957	-0.04511	-0.03662	-0.0979	-0.08981	-0.16315	-0.1562852	-0.3242	-0.35301
Molar Density	lbmol/cuft	3.400764	0.004445	0.004255	0.009674	0.011686	0.026621	0.035598	0.080689	0.124831	0.2669525	0.954759	0.920747
Mass Density	lb/cuft	61.26572	0.124115	0.186489	0.424015	0.512237	1.166837	1.560331	3.536799	5.4716	11.701122	41.8492	40.35837
Enthalpy Flow	Btu/hr	-6.61E+09	-2E+09	-1.2E+09	-1.2E+09	-1.2E+09	-1.2E+09	-1.2E+09	-1.2E+09	-1.2E+09	-1.189E+09	-1.2E+09	-1.2E+09
Average MW		18.01528	27.92288	43.83223	43.83223	43.83223	43.83223	43.83223	43.83223	43.83223	43.832226	43.83223	43.83223
Mole Flows	lbmol/hr	53609.72	223689	7140.923	7140.923	7140.923	7140.923	7140.923	7140.923	7140.923	7140.9234	7140.923	7140.923
OXYGEN	lbmol/hr	0	31134	0	0	0	0	0	0	0	0	0	0
NITROGEN	lbmol/hr	0	176077.8	79.27068	79.27068	79.27068	79.27068	79.27068	79.27068	79.27068	79.270677	79.27068	79.27068
METHANE	lbmol/hr	0	0	0	0	0	0	0	0	0	0	0	0
WATER	lbmol/hr	53609.72	15692.56	0	0	0	0	0	0	0	0	0	0
CARBO-01	lbmol/hr	0	784.6281	7061.653	7061.653	7061.653	7061.653	7061.653	7061.653	7061.653	7061.6527	7061.653	7061.653
Mole Fractions													
OXYGEN		0	0.139184	0	0	0	0	0	0	0	0	0	0
NITROGEN		0	0.787155	0.011101	0.011101	0.011101	0.011101	0.011101	0.011101	0.011101	0.0111009	0.011101	0.011101
METHANE		0	0	0	0	0	0	0	0	0	0	0	0
WATER		1	0.070153	0	0	0	0	0	0	0	0	0	0
CARBO-01		0	0.003508	0.988899	0.988899	0.988899	0.988899	0.988899	0.988899	0.988899	0.9888991	0.988899	0.988899
Mass Flows	tons/hr	482.8971	3123.02	156.5013	156.5013	156.5013	156.5013	156.5013	156.5013	156.5013	156.50129	156.5013	156.5013
OXYGEN	tons/hr	0	498.1253	0	0	0	0	0	0	0	0	0	0
NITROGEN	tons/hr	0	2466.276	1.110324	1.110324	1.110324	1.110324	1.110324	1.110324	1.110324	1.1103238	1.110324	1.110324
METHANE	tons/hr	0	0	0	0	0	0	0	0	0	0	0	0
WATER	tons/hr	482.8971	141.3529	0	0	0	0	0	0	0	0	0	0
CARBO-01	tons/hr	0	17.26566	155.391	155.391	155.391	155.391	155.391	155.391	155.391	155.39096	155.391	155.391
Mass Fractions													
OXYGEN		0	0.159501	0	0	0	0	0	0	0	0	0	0
NITROGEN		0	0.789709	0.007095	0.007095	0.007095	0.007095	0.007095	0.007095	0.007095	0.0070947	0.007095	0.007095
METHANE		0	0	0	0	0	0	0	0	0	0	0	0
WATER		1	0.045262	0	0	0	0	0	0	0	0	0	0
CARBO-01		0	0.005529	0.992905	0.992905	0.992905	0.992905	0.992905	0.992905	0.992905	0.9929053	0.992905	0.992905
Volume Flow	cuft/min	262.7337	838740.8	27973.24	12303.13	10184.18	4470.812	3343.336	1474.981	953.4158	445.82984	124.6549	129.2597
Vapor Phase													
Molar Enthalpy	Btu/lbmol		-2742.71	-167250	-165663	-167174	-165570	-167331	-165798	-167878	-166562.99	-171181	
Mass Enthalpy	Btu/lb		-96.413	-3815.68	-3779.47	-3813.94	-3777.37	-3817.53	-3782.57	-3830.02	-3800.0121	-3905.36	
Molar Entropy	Btu/lbmol-R		-0.0738	-0.11641	0.261126	-1.97734	-1.60535	-4.29111	-3.93664	-7.15123	-6.8503289	-14.2102	
Mass Entropy	Btu/lb-R		-0.00259	-0.00266	0.005957	-0.04511	-0.03662	-0.0979	-0.08981	-0.16315	-0.1562852	-0.3242	
Molar Density	lbmol/cuft		0.004222	0.004255	0.009674	0.011686	0.026621	0.035598	0.080689	0.124831	0.2669525	0.954759	
Mass Density	lb/cuft		0.120096	0.186489	0.424015	0.512237	1.166837	1.560331	3.536799	5.4716	11.701122	41.8492	
Enthalpy Flow	Btu/hr		-5.8E+08	-1.2E+09	-1.2E+09	-1.2E+09	-1.2E+09	-1.2E+09	-1.2E+09	-1.2E+09	-1.189E+09	-1.2E+09	
Average MW			28.4475	43.83223	43.83223	43.83223	43.83223	43.83223	43.83223	43.83223	43.832226	43.83223	
Mole Flows	lbmol/hr		212439.8	7140.923	7140.923	7140.923	7140.923	7140.923	7140.923	7140.923	7140.9234	7140.923	
Mass Flows	tons/hr		3021.691	156.5013	156.5013	156.5013	156.5013	156.5013	156.5013	156.5013	156.50129	156.5013	
Volume Flow	cuft/hr		50321167	1678394	738188	611050.9	268248.7	200600.1	88498.84	57204.95	26749.791	7479.296	
Liquid Phase													
Molar Enthalpy	Btu/lbmol	-123233.2	-123531										-171876
Mass Enthalpy	Btu/lb	-6840.482	-6856.99										-3921.23
Molar Entropy	Btu/lbmol-R	-39.30246	-39.7963										-15.4734
Mass Entropy	Btu/lb-R	-2.181618	-2.20903										-0.35301
Molar Density	lbmol/cuft	3.400764	3.427576										0.920747
Mass Density	lb/cuft	61.26572	61.74879										40.35837
Enthalpy Flow	Btu/hr	-6.61E+09	-1.4E+09										-1.2E+09
Mole Flows	lbmol/hr	53609.72	11249.18										7140.923
Mass Flows	tons/hr	482.8971	101.3287										156.5013
Volume Flow	cuft/hr	15764.02	3281.965										7755.58

28.20. Allam Cycle Aspen Input



DYNAMICS

DYNAMICS RESULTS=ON

IN UNITS ENG SHORT-LENGTH=in

DEF-STREAMS CONVEN ALL

MODEL-OPTION

DATABANKS 'APV110 PURE37' / 'APV110 AQUEOUS' / 'APV110 SOLIDS' &

/ 'APV110 INORGANIC' / 'APESV110 AP-EOS' / &

'NISTV110 NIST-TRC' / NOASPENPCD

PROP-SOURCES 'APV110 PURE37' / 'APV110 AQUEOUS' / &

'APV110 SOLIDS' / 'APV110 INORGANIC' / 'APESV110 AP-EOS' &

/ 'NISTV110 NIST-TRC'

COMPONENTS

METHANE CH4 /

CO2 /

OXYGEN O2 /

NITROGEN N2 /

WATER H2O

SOLVE

RUN-MODE MODE=SIM

FLOWSHEET

BLOCK NG-COMP1 IN=301 OUT=301A

BLOCK COMBUST IN=319 325 302 OUT=303

BLOCK TURBINE IN=303 OUT=304

BLOCK SPLIT1 IN=311 OUT=314 312

BLOCK SPLIT2 IN=315 OUT=316 320

```
  BLOCK MIX IN=320 321 OUT=322
  BLOCK CO2PUMP IN=316 OUT=317
  BLOCK RECU IN=304 318 324 OUT=305 319 325
  BLOCK NG-COMP2 IN=301B OUT=302
  BLOCK INTCOOL1 IN=301A OUT=301B
  BLOCK O2PUMP IN=322 OUT=323
  BLOCK SEPARATE IN=307 OUT=310 308
  BLOCK CO2COMP1 IN=310 OUT=310B
  BLOCK CO2COMP2 IN=310C OUT=310D
  BLOCK CO2COMP3 IN=310E OUT=310F
  BLOCK INTCOOL2 IN=310B OUT=310C
  BLOCK INTCOOL3 IN=310D OUT=310E
  BLOCK INTCOOL4 IN=310F OUT=310G
  BLOCK VALVE IN=306 OUT=307
  BLOCK INTCOOL5 IN=310H OUT=311
  BLOCK CO2COMP4 IN=310G OUT=310H
  BLOCK ASUHEAT1 IN=317 OUT=318
  BLOCK ASUHEAT2 IN=323 OUT=324
  BLOCK COOLER2 IN=312 308 OUT=313 309
  BLOCK COOLER1 IN=305 OUT=306
  BLOCK COOLER3 IN=314 CW-IN OUT=315 CW-OUT
PROPERTIES SRK FREE-WATER=STEAMNBS
STREAM 301
  SUBSTREAM MIXED TEMP=100. PRES=465. MOLE-FLOW=7726.
  MOLE-FRAC METHANE 1.
STREAM 319
  SUBSTREAM MIXED TEMP=1269.83 PRES=4336.4 <psig>  &
    MOLE-FLOW=127584.03
  MOLE-FRAC CO2 0.988584 / OXYGEN 1E-06 / NITROGEN  &
    0.00996553 / WATER 0.00144979
STREAM 321
  SUBSTREAM MIXED TEMP=90. PRES=1726. <psig>  &
    MOLE-FLOW=15529.648
  MOLE-FRAC OXYGEN 0.995 / NITROGEN 0.005
```

```
STREAM 325
   SUBSTREAM MIXED TEMP=1269.83 PRES=4336.4 <psig>  &
      MOLE-FLOW=103019.0288
   MOLE-FRAC CO2 0.8395594 / OXYGEN 0.149992 / NITROGEN  &
      0.009217 / WATER 0.00123124
STREAM CW-IN
   SUBSTREAM MIXED TEMP=90. PRES=0. <psig>  &
      VOLUME-FLOW=25000. <gal/min>
   MOLE-FRAC WATER 1.
BLOCK MIX MIXER
   PARAM
BLOCK SPLIT1 FSPLIT
   FRAC 314 0.965
BLOCK SPLIT2 FSPLIT
   FRAC 320 0.406788
BLOCK ASUHEAT1 HEATER
   PARAM TEMP=170. PRES=0. DPPARMOPT=NO
BLOCK ASUHEAT2 HEATER
   PARAM TEMP=170. PRES=0. DPPARMOPT=NO
BLOCK COOLER1 HEATER
   PARAM TEMP=92. PRES=0. DPPARMOPT=NO
BLOCK INTCOOL1 HEATER
   PARAM TEMP=100. PRES=1390. DPPARMOPT=NO
BLOCK INTCOOL2 HEATER
   PARAM TEMP=100. PRES=392. DPPARMOPT=NO
BLOCK INTCOOL3 HEATER
   PARAM TEMP=100. PRES=626. DPPARMOPT=NO
BLOCK INTCOOL4 HEATER
   PARAM TEMP=100. PRES=1003. DPPARMOPT=NO
BLOCK INTCOOL5 HEATER
   PARAM TEMP=100. PRES=1731. <psig> DPPARMOPT=NO
BLOCK SEPARATE FLASH2
   PARAM TEMP=71.24 PRES=231.8 <psig>
BLOCK COOLER2 HEATX
```

```
  PARAM T-HOT=80. PRES-HOT=1726. <psig>
  FEEDS HOT=312 COLD=308
  OUTLETS-HOT 313
  OUTLETS-COLD 309
  HOT-SIDE DPPARMOPT=NO
  COLD-SIDE DPPARMOPT=NO
  TQ-PARAM CURVE=YES
BLOCK COOLER3 HEATX
  PARAM T-HOT=95.
  FEEDS HOT=314 COLD=CW-IN
  OUTLETS-HOT 315
  OUTLETS-COLD CW-OUT
  HOT-SIDE DPPARMOPT=NO
  COLD-SIDE DPPARMOPT=NO
  TQ-PARAM CURVE=YES
BLOCK RECU MHEATX
  HOT-SIDE IN=304 OUT=305 TEMP=188. PRES=415.4 <psig>  &
    FREE-WATER=NO DPPARMOPT=NO
  COLD-SIDE IN=318 OUT=319 PRES=4336.4 <psig> FREE-WATER=NO  &
    DPPARMOPT=NO
  COLD-SIDE IN=324 OUT=325 PRES=4336.4 <psig> FREE-WATER=NO  &
    DPPARMOPT=NO
  PARAM NPOINT=50 ADAPTIVE-GRI=YES
BLOCK COMBUST RSTOIC
  PARAM PRES=4336.4 <psig> DUTY=0. HEAT-OF-REAC=YES
  STOIC 1 MIXED METHANE -1. / OXYGEN -2. / CO2 1. /  &
    WATER 2.
  CONV 1 MIXED METHANE 1.
  HEAT-RXN REACNO=1 CID=METHANE
BLOCK CO2PUMP PUMP
  PARAM PRES=4341.4 <psig> EFF=0.85
BLOCK O2PUMP PUMP
  PARAM PRES=4341.4 <psig> EFF=0.85
```

```
BLOCK CO2COMP1 COMPR
   PARAM TYPE=ASME-POLYTROP PRATIO=1.61 PEFF=0.85 SB-MAXIT=30  &
      SB-TOL=0.0001
BLOCK CO2COMP2 COMPR
   PARAM TYPE=ASME-POLYTROP PRATIO=1.61 PEFF=0.85 SB-MAXIT=30  &
      SB-TOL=0.0001
BLOCK CO2COMP3 COMPR
   PARAM TYPE=ASME-POLYTROP PRATIO=1.61 PEFF=0.85 SB-MAXIT=30  &
      SB-TOL=0.0001
BLOCK CO2COMP4 COMPR
   PARAM TYPE=ASME-POLYTROP PRES=1731. <psig> PEFF=0.85  &
      SB-MAXIT=30 SB-TOL=0.0001
BLOCK NG-COMP1 COMPR
   PARAM TYPE=ASME-POLYTROP PRATIO=3. PEFF=0.85 SB-MAXIT=30  &
      SB-TOL=0.0001
BLOCK NG-COMP2 COMPR
   PARAM TYPE=ASME-POLYTROP PRES=4336.4 <psig> PEFF=0.85  &
      SB-MAXIT=30 SB-TOL=0.0001
BLOCK TURBINE COMPR
   PARAM TYPE=ASME-POLYTROP PRES=420.4 <psig> PEFF=0.85  &
      SB-MAXIT=30 SB-TOL=0.0001 MODEL-TYPE=TURBINE
BLOCK VALVE
   PARAM P-OUT=231.8 <psig>
EO-CONV-OPTI
STREAM-REPOR MOLEFLOW
PROPERTY-REP PCES
```

28.21. Allam Cycle Full Aspen Stream Report

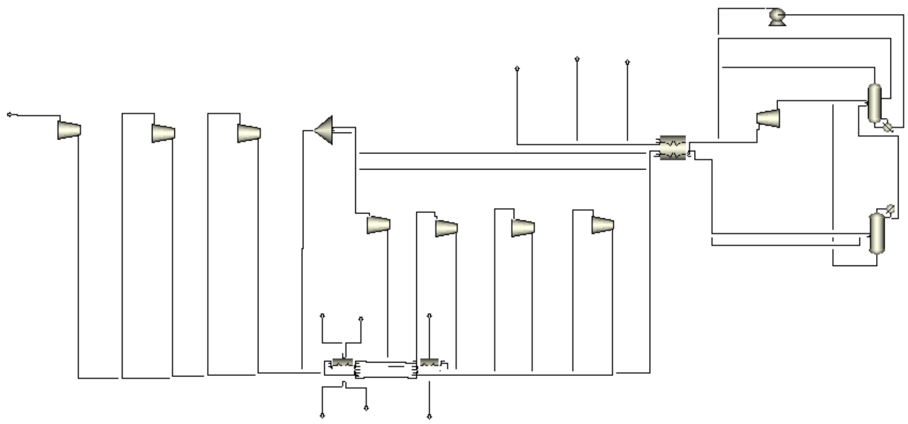
All stream numbers match number in report. Streams with letter (B, C, D, ...) indicate an intermediate stream for compressor intercooling. CW-In & CW-Out is cw for Cooler3.

	Units	301	301A	301B	302	303	304	305	306	307	308	309	310
Description													
From			NG-COMP	INTCOOL1	NG-COMP	COMBUST	TURBINE	RECU	COOLER1	VALVE	SEPARATE	COOLER2	SEPARATE
To		NG-COMP	INTCOOL1	NG-COMP	COMBUST	TURBINE	RECU	COOLER1	VALVE	SEPARATE	COOLER2		CO2COMP
Stream Class		CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN
Maximum Relative Error													
Cost Flow	$/hr												
MIXED Substream													
Phase		Vapor Pha	Vapor Pha	Vapor Pha	Vapor Pha	Vapor Pha	Vapor Phase				Liquid Pha	Liquid Pha	Vapor Pha
Temperature	F	100	287.3609	100	293.4625	2061.501	1421.367	188	92	71.24011	71.24	87.87713	71.24
Pressure	psig	450.3041	1380.304	1375.304	4336.4	4336.4	420.4	415.4	415.4	231.8	231.8	231.8	231.8
Molar Vapor Fraction		1	1	1	1	1	1	0.956638	0.93563	0.935152	0	0	1
Molar Liquid Fraction		0	0	0	0	0	0	0.043362	0.06437	0.064848	1	1	0
Molar Solid Fraction		0	0	0	0	0	0	0	0	0	0	0	0
Mass Vapor Fraction		1	1	1	1	1	1	0.981397	0.972416	0.97224	0	0	1
Mass Liquid Fraction		0	0	0	0	0	0	0.018603	0.027584	0.02776	1	1	0
Mass Solid Fraction		0	0	0	0	0	0	0	0	0	0	0	0
Molar Enthalpy	Btu/lbmol	-32053.4	-30433.8	-32464.4	-30775	-139380	-148174	-163463	-164949	-164949	-124335	-123990	-167765
Mass Enthalpy	Btu/lb	-1998	-1897.04	-2023.62	-1918.31	-3307.44	-3516.11	-3878.91	-3914.18	-3914.18	-6892.32	-6873.21	-3829.15
Molar Entropy	Btu/lbmol	-26.0422	-25.6714	-28.7951	-28.4141	6.667992	7.372072	-6.01961	-8.4316	-7.5092	-39.1258	-38.5714	-5.31675
Mass Entropy	Btu/lb-R	-1.6233	-1.60018	-1.7949	-1.77115	0.158229	0.174937	-0.14284	-0.20008	-0.17819	-2.16888	-2.13815	-0.12135
Molar Density	lbmol/cuft	0.080914	0.175749	0.258677	0.50447	0.149689	0.021373	0.07031	0.090692	0.050862	3.338249	3.31081	0.047611
Mass Density	lb/cuft	1.298081	2.819505	4.149893	8.093083	6.308087	0.900708	2.962948	3.821896	2.143385	60.2207	59.72571	2.085947
Enthalpy Flow	Btu/hr	-2.5E+08	-2.4E+08	-2.5E+08	-2.4E+08	-3.3E+10	-3.5E+10	-3.9E+10	-3.9E+10	-3.9E+10	-1.9E+09	-1.9E+09	-3.7E+10
Average MW		16.04276	16.04276	16.04276	16.04276	42.14137	42.14137	42.14137	42.14137	42.14137	18.03961	18.03961	43.8127
Mole Flows	lbmol/hr	7726	7726	7726	7726	238329.1	238329.1	238329.1	238329.1	238329.1	15455.16	15455.16	222873.9
METHANE	lbmol/hr	7726	7726	7726	7726	0	0	0	0	0	0.00E+00	0.00E+00	0
CO2	lbmol/hr	0	0	0	0	220344.1	220344.1	220344.1	220344.1	220344.1	14.4639	14.4639	220329.7
OXYGEN	lbmol/hr	0	0	0	0	0.163314	0.163314	0.163314	0.163314	0.163314	2.94E-07	2.94E-07	0.163314
NITROGEN	lbmol/hr	0	0	0	0	2220.969	2220.969	2220.969	2220.969	2220.969	0.000151	0.000151	2220.969
WATER	lbmol/hr	0	0	0	0	15763.81	15763.81	15763.81	15763.81	15763.81	15440.69	15440.69	323.1199
Mole Fractions													
METHANE		1	1	1	1	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CO2		0	0	0	0	0.924537	0.924537	0.924537	0.924537	0.924537	0.000936	0.000936	0.988584
OXYGEN		0	0	0	0	6.85E-07	6.85E-07	6.85E-07	6.85E-07	6.85E-07	1.91E-11	1.91E-11	7.33E-07
NITROGEN		0	0	0	0	0.009319	0.009319	0.009319	0.009319	0.009319	9.78E-09	9.78E-09	0.009965
WATER		0	0	0	0	0.066143	0.066143	0.066143	0.066143	0.066143	0.999064	0.999064	0.00145
Mass Flows	tons/hr	61.97318	61.97318	61.97318	61.97318	5021.756	5021.756	5021.756	5021.756	5021.756	139.4025	139.4025	4882.354
METHANE	tons/hr	61.97318	61.97318	61.97318	61.97318	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CO2	tons/hr	0	0	0	0	4848.65	4848.65	4848.65	4848.65	4848.65	0.318277	0.318277	4848.332
OXYGEN	tons/hr	0	0	0	0	0.002613	0.002613	0.002613	0.002613	0.002613	4.71E-09	4.71E-09	0.002613
NITROGEN	tons/hr	0	0	0	0	31.10853	31.10853	31.10853	31.10853	31.10853	2.12E-06	2.12E-06	31.10853
WATER	tons/hr	0	0	0	0	141.9947	141.9947	141.9947	141.9947	141.9947	139.0842	139.0842	2.910548
Mass Fractions													
METHANE		1	1	1	1	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CO2		0	0	0	0	0.965529	0.965529	0.965529	0.965529	0.965529	0.002283	0.002283	0.993032
OXYGEN		0	0	0	0	5.20E-07	5.20E-07	5.20E-07	5.20E-07	5.20E-07	3.38E-11	3.38E-11	5.35E-07
NITROGEN		0	0	0	0	0.006195	0.006195	0.006195	0.006195	0.006195	1.52E-08	1.52E-08	0.006372
WATER		0	0	0	0	0.028276	0.028276	0.028276	0.028276	0.028276	0.997717	0.997717	0.000596
Volume Flow	cuft/min	1591.405	732.672	497.7894	255.2516	26536.08	185844.8	56495.03	43798.12	78096.95	77.16199	77.80149	78019.77
Vapor Phase													
Molar Enthalpy	Btu/lbmol	-32053.4	-30433.8	-32464.4	-30775	-139380	-148174	-165343	-167771	-167765			-167765
Mass Enthalpy	Btu/lb	-1998	-1897.04	-2023.62	-1918.31	-3307.44	-3516.11	-3824.56	-3830.55	-3829.15			-3829.15
Molar Entropy	Btu/lbmol	-26.0422	-25.6714	-28.7951	-28.4141	6.667992	7.372072	-4.68319	-6.36904	-5.31675			-5.31675
Mass Entropy	Btu/lb-R	-1.6233	-1.60018	-1.7949	-1.77115	0.158229	0.174937	-0.10833	-0.14542	-0.12135			-0.12135
Molar Density	lbmol/cuft	0.080914	0.175749	0.258677	0.50447	0.149689	0.021373	0.067327	0.085005	0.047611			0.047611
Mass Density	lb/cuft	1.298081	2.819505	4.149893	8.093083	6.308087	0.900708	2.910667	3.723055	2.085947			2.085947
Enthalpy Flow	Btu/hr	-2.5E+08	-2.4E+08	-2.5E+08	-2.4E+08	-3.3E+10	-3.5E+10	-3.8E+10	-3.7E+10	-3.7E+10			-3.7E+10
Average MW		16.04276	16.04276	16.04276	16.04276	42.14137	42.14137	43.23204	43.79823	43.8127			43.8127
Mole Flows	lbmol/hr	7726	7726	7726	7726	238329.1	238329.1	227994.5	222987.9	222873.9			222873.9
Mass Flows	lb/hr	123946.4	123946.4	123946.4	123946.4	10043512	10043512	9856668	9766475	9764707			9764707
Volume Flow	cuft/hr	95484.3	43960.32	29867.36	15315.1	1592165	11150685	3386395	2623242	4681188			4681186
Liquid Phase													
Molar Enthalpy	Btu/lbmol							-121973	-123926	-124335	-124335	-123990	
Mass Enthalpy	Btu/lb							-6746.44	-6862.49	-6892.32	-6892.32	-6873.21	
Molar Entropy	Btu/lbmol-R							-35.503	-38.4114	-39.1258	-39.1258	-38.5714	
Mass Entropy	Btu/lb-R							-1.96371	-2.12707	-2.16888	-2.16888	-2.13815	
Molar Density	lbmol/cuft							3.125042	3.302752	3.338249	3.338249	3.31081	
Mass Density	lb/cuft							56.49954	59.64248	60.2207	60.2207	59.72571	
Enthalpy Flow	Btu/hr							-1.3E+09	-1.9E+09	-1.9E+09	-1.9E+09	-1.9E+09	
Average MW								18.07961	18.05842	18.03961	18.03961	18.03961	
Mole Flows	lbmol/hr							10334.53	15341.15	15455.15	15455.16	15455.16	
Mass Flows	lb/hr							186844.3	277037	278804.9	278804.9	278804.9	
Volume Flow	cuft/hr							3307.005	4644.961	4629.719	4629.719	4668.089	

	Units	310B	310C	310D	310E	310F	310G	310H	311	312	313	314	315
Description													
From		CO2COMF	INTCOOL2	CO2COMF	INTCOOL3	CO2COMF	INTCOOL4	CO2COMF	INTCOOL5	SPLIT1	COOLER2	SPLIT1	COOLER3
To		INTCOOL2	CO2COMF	INTCOOL3	CO2COMF	INTCOOL4	CO2COMF	INTCOOL5	SPLIT1	COOLER2		COOLER3	SPLIT2
Stream Class		CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN
Maximum Relative Error													
Cost Flow	$/hr												
MIXED Substream													
Phase		Vapor Pha	Vapor Pha	Vapor Pha	Vapor Pha	Vapor Pha	Vapor Pha	Vapor Pha	Liquid Pha	Liquid Pha	Liquid Pha	Liquid Pha	Liquid Pha
Temperature	F	144.2205	100	176.548	100	177.901	100	184.2535	100	100	80	100	95
Pressure	psig	382.1625	377.3041	616.4241	611.3041	993.1641	988.3041	1731	1731	1731	1726	1731	1731
Molar Vapor Fraction		1	1	1	1	1	1	1	0	0	0	0	0
Molar Liquid Fraction		0	0	0	0	0	0	0	1	1	1	1	1
Molar Solid Fraction		0	0	0	0	0	0	0	0	0	0	0	0
Mass Vapor Fraction		1	1	1	1	1	1	1	0	0	0	0	0
Mass Liquid Fraction		0	0	0	0	0	0	0	1	1	1	1	1
Mass Solid Fraction		0	0	0	0	0	0	0	0	0	0	0	0
Molar Enthalpy	Btu/lbmol	-167193	-167665	-167083	-168011	-167483	-168810	-168314	-171286	-171286	-171969	-171286	-171471
Mass Enthalpy	Btu/lb	-3816.09	-3826.85	-3813.56	-3834.76	-3822.7	-3853	-3841.68	-3909.51	-3909.51	-3925.09	-3909.51	-3913.72
Molar Entropy	Btu/lbmol	-5.16544	-5.95453	-5.80844	-7.35201	-7.21969	-9.44611	-9.32308	-14.2966	-14.2966	-15.5414	-14.2966	-14.6295
Mass Entropy	Btu/lb-R	-0.1179	-0.13591	-0.13257	-0.16781	-0.16479	-0.2156	-0.21279	-0.32631	-0.32631	-0.35472	-0.32631	-0.33391
Molar Density	lbmol/cuft	0.067561	0.074502	0.105412	0.132003	0.183968	0.275044	0.376125	0.916107	0.916107	1.067588	0.916107	0.957441
Mass Density	lb/cuft	2.960023	3.264138	4.618364	5.783425	8.060128	12.05041	16.47904	40.1371	40.1371	46.77393	40.1371	41.94808
Enthalpy Flow	Btu/hr	-3.7E+10	-3.7E+10	-3.7E+10	-3.7E+10	-3.7E+10	-3.8E+10	-3.8E+10	-3.8E+10	-1.3E+09	-1.3E+09	-3.7E+10	-3.7E+10
Average MW		43.8127	43.8127	43.8127	43.8127	43.8127	43.8127	43.8127	43.8127	43.8127	43.8127	43.8127	43.8127
Mole Flows	lbmol/hr	222873.9	222873.9	222873.9	222873.9	222873.9	222873.9	222873.9	222873.9	7800.587	7800.587	215073.3	215073.3
METHANE	lbmol/hr	0	0	0	0	0	0	0	0	0.00E+00	0.00E+00	0	0
CO2	lbmol/hr	220329.7	220329.7	220329.7	220329.7	220329.7	220329.7	220329.7	220329.7	7711.538	7711.538	212618.1	212618.1
OXYGEN	lbmol/hr	0.163314	0.163314	0.163314	0.163314	0.163314	0.163314	0.163314	0.163314	0.005716	0.005716	0.157598	0.157598
NITROGEN	lbmol/hr	2220.969	2220.969	2220.969	2220.969	2220.969	2220.969	2220.969	2220.969	77.7339	77.7339	2143.235	2143.235
WATER	lbmol/hr	323.1199	323.1199	323.1199	323.1199	323.1199	323.1199	323.1199	323.1199	11.3092	11.3092	311.8107	311.8107
Mole Fractions													
METHANE		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CO2		0.988584	0.988584	0.988584	0.988584	0.988584	0.988584	0.988584	0.988584	0.988584	0.988584	0.988584	0.988584
OXYGEN		7.33E-07	7.33E-07	7.33E-07	7.33E-07	7.33E-07	7.33E-07	7.33E-07	7.33E-07	7.33E-07	7.33E-07	7.33E-07	7.33E-07
NITROGEN		0.009965	0.009965	0.009965	0.009965	0.009965	0.009965	0.009965	0.009965	0.009965	0.009965	0.009965	0.009965
WATER		0.00145	0.00145	0.00145	0.00145	0.00145	0.00145	0.00145	0.00145	0.00145	0.00145	0.00145	0.00145
Mass Flows	tons/hr	4882.354	4882.354	4882.354	4882.354	4882.354	4882.354	4882.354	4882.354	170.8824	170.8824	4711.471	4711.471
METHANE	tons/hr	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CO2	tons/hr	4848.332	4848.332	4848.332	4848.332	4848.332	4848.332	4848.332	4848.332	169.6916	169.6916	4678.64	4678.64
OXYGEN	tons/hr	0.002613	0.002613	0.002613	0.002613	0.002613	0.002613	0.002613	0.002613	9.15E-05	9.15E-05	0.002521	0.002521
NITROGEN	tons/hr	31.10853	31.10853	31.10853	31.10853	31.10853	31.10853	31.10853	31.10853	1.088799	1.088799	30.01973	30.01973
WATER	tons/hr	2.910548	2.910548	2.910548	2.910548	2.910548	2.910548	2.910548	2.910548	0.101869	0.101869	2.808679	2.808679
Mass Fractions													
METHANE		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CO2		0.993032	0.993032	0.993032	0.993032	0.993032	0.993032	0.993032	0.993032	0.993032	0.993032	0.993032	0.993032
OXYGEN		5.35E-07	5.35E-07	5.35E-07	5.35E-07	5.35E-07	5.35E-07	5.35E-07	5.35E-07	5.35E-07	5.35E-07	5.35E-07	5.35E-07
NITROGEN		0.006372	0.006372	0.006372	0.006372	0.006372	0.006372	0.006372	0.006372	0.006372	0.006372	0.006372	0.006372
WATER		0.000596	0.000596	0.000596	0.000596	0.000596	0.000596	0.000596	0.000596	0.000596	0.000596	0.000596	0.000596
Volume Flow	cuft/min	54981.04	49858.53	35238.7	28139.92	20191.38	13505.36	9875.886	4054.73	141.9156	121.7789	3912.815	3743.891
Vapor Phase													
Molar Enthalpy	Btu/lbmol	-167193	-167665	-167083	-168011	-167483	-168810	-168314					
Mass Enthalpy	Btu/lb	-3816.09	-3826.85	-3813.56	-3834.76	-3822.7	-3853	-3841.68					
Molar Entropy	Btu/lbmol	-5.16544	-5.95453	-5.80844	-7.35201	-7.21969	-9.44611	-9.32308					
Mass Entropy	Btu/lb-R	-0.1179	-0.13591	-0.13257	-0.16781	-0.16479	-0.2156	-0.21279					
Molar Density	lbmol/cuft	0.067561	0.074502	0.105412	0.132003	0.183968	0.275044	0.376125					
Mass Density	lb/cuft	2.960023	3.264138	4.618364	5.783425	8.060128	12.05041	16.47904					
Enthalpy Flow	Btu/hr	-3.7E+10	-3.7E+10	-3.7E+10	-3.7E+10	-3.7E+10	-3.8E+10	-3.8E+10					
Average MW		43.8127	43.8127	43.8127	43.8127	43.8127	43.8127	43.8127					
Mole Flows	lbmol/hr	222873.9	222873.9	222873.9	222873.9	222873.9	222873.9	222873.9					
Mass Flows	lb/hr	9764707	9764707	9764707	9764707	9764707	9764707	9764707					
Volume Flow	cuft/hr	3298862	2991512	2114322	1688395	1211483	810321.5	592553.2					
Liquid Phase													
Molar Enthalpy	Btu/lbmol								-171286	-171286	-171969	-171286	-171471
Mass Enthalpy	Btu/lb								-3909.51	-3909.51	-3925.09	-3909.51	-3913.72
Molar Entropy	Btu/lbmol-R								-14.2966	-14.2966	-15.5414	-14.2966	-14.6295
Mass Entropy	Btu/lb-R								-0.32631	-0.32631	-0.35472	-0.32631	-0.33391
Molar Density	lbmol/cuft								0.916107	0.916107	1.067588	0.916107	0.957441
Mass Density	lb/cuft								40.1371	40.1371	46.77393	40.1371	41.94808
Enthalpy Flow	Btu/hr								-3.8E+10	-1.3E+09	-1.3E+09	-3.7E+10	-3.7E+10
Average MW									43.8127	43.8127	43.8127	43.8127	43.8127
Mole Flows	lbmol/hr								222873.9	7800.587	7800.587	215073.3	215073.3
Mass Flows	lb/hr								9764707	341764.8	341764.8	9422943	9422943
Volume Flow	cuft/hr								243283.8	8514.933	7306.735	234768.9	224633.5

	Units	316	317	318	319	320	321	322	323	324	325	CW-IN	CW-OUT
Description													
From		SPLIT2	CO2PUMP	ASUHEAT1	RECU	SPLIT2		MIX	O2PUMP	ASUHEAT2	RECU		COOLER3
To		CO2PUMP	ASUHEAT1	RECU	COMBUST	MIX	MIX	O2PUMP	ASUHEAT2	RECU	COMBUST	COOLER3	
Stream Class		CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN
Maximum Relative Error													
Cost Flow	$/hr												
MIXED Substream													
Phase		Liquid Pha	Liquid Pha	Liquid Pha	Vapor Pha	Liquid Pha	Vapor Pha	Liquid Pha	Liquid Pha	Vapor Pha	Vapor Pha	Liquid Pha	Liquid Pha
Temperature	F	95	149.3135	170	1269.838	95	90	74.72	143.5846	170	1269.838	90	92.89055
Pressure	psig	1731	4341.4	4341.4	4336.4	1731	1726	1726	4341.4	4341.4	4336.4	-1.78E-15	-1.78E-15
Molar Vapor Fraction		0	0	0	1	0	1	0	0	1	1	0	0
Molar Liquid Fraction		1	1	1	0	1	0	1	1	0	0	1	1
Molar Solid Fraction		0	0	0	0	0	0	0	0	0	0	0	0
Mass Vapor Fraction		0	0	0	1	0	1	0	0	1	1	0	0
Mass Liquid Fraction		1	1	1	0	1	0	1	1	0	0	1	1
Mass Solid Fraction		0	0	0	0	0	0	0	0	0	0	0	0
Molar Enthalpy	Btu/lbmol	-171471	-170877	-170417	-154030	-171471	-275.923	-145664	-145003	-144457	-129382	-123919	-123859
Mass Enthalpy	Btu/lb	-3913.72	-3900.18	-3889.67	-3515.64	-3913.72	-8.62828	-3465.81	-3450.09	-3437.1	-3078.42	-6878.54	-6875.21
Molar Entropy	Btu/lbmol	-14.6295	-14.4727	-13.7305	2.005787	-14.6295	-9.83062	-13.2824	-13.0763	-12.1899	2.17983	-38.5367	-38.4423
Mass Entropy	Btu/lb-R	-0.33391	-0.33033	-0.31339	0.045781	-0.33391	-0.30741	-0.31603	-0.31113	-0.29004	0.051865	-2.13911	-2.13387
Molar Density	lbmol/cuft	0.957441	1.089708	1.015924	0.214137	0.957441	0.304308	0.861593	1.018285	0.891095	0.214424	3.30876	3.303884
Mass Density	lb/cuft	41.94808	47.74303	44.51037	9.381913	41.94808	9.731419	36.2117	42.79728	37.45164	9.01199	59.60824	59.5204
Enthalpy Flow	Btu/hr	-2.2E+10	-2.2E+10	-2.2E+10	-2E+10	-1.5E+10	-4284980	-1.5E+10	-1.5E+10	-1.5E+10	-1.3E+10	-8.2E+10	-8.2E+10
Average MW		43.8127	43.8127	43.8127	43.8127	43.8127	31.97887	42.0288	42.0288	42.0288	42.0288	18.01528	18.01528
Mole Flows	lbmol/hr	127584.1	127584.1	127584.1	127584.1	87489.24	15529.65	103018.9	103018.9	103018.9	103018.9	663475.4	663475.4
METHANE	lbmol/hr	0	0	0	0	0	0	0	0	0	0	0	0
CO2	lbmol/hr	126127.6	126127.6	126127.6	126127.6	86490.5	0	86490.5	86490.5	86490.5	86490.5	0	0
OXYGEN	lbmol/hr	0.093489	0.093489	0.093489	0.093489	0.064109	15452	15452.06	15452.06	15452.06	15452.06	0	0
NITROGEN	lbmol/hr	1271.393	1271.393	1271.393	1271.393	871.8422	77.64824	949.4904	949.4904	949.4904	949.4904	0	0
WATER	lbmol/hr	184.9699	184.9699	184.9699	184.9699	126.8409	0	126.8409	126.8409	126.8409	126.8409	663475.4	663475.4
Mole Fractions													
METHANE		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0	0
CO2		0.988584	0.988584	0.988584	0.988584	0.988584	0	0.83956	0.83956	0.83956	0.83956	0	0
OXYGEN		7.33E-07	7.33E-07	7.33E-07	7.33E-07	7.33E-07	0.995	0.149993	0.149993	0.149993	0.149993	0	0
NITROGEN		0.009965	0.009965	0.009965	0.009965	0.009965	0.005	0.009217	0.009217	0.009217	0.009217	0	0
WATER		0.00145	0.00145	0.00145	0.00145	0.00145	0	0.001231	0.001231	0.001231	0.001231	1	1
Mass Flows	tons/hr	2794.901	2794.901	2794.901	2794.901	1916.57	248.3103	2164.88	2164.88	2164.88	2164.88	5976.347	5976.347
METHANE	tons/hr	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0	0
CO2	tons/hr	2775.426	2775.426	2775.426	2775.426	1903.215	0	1903.215	1903.215	1903.215	1903.215	0	0
OXYGEN	tons/hr	0.001496	0.001496	0.001496	0.001496	0.001026	247.2227	247.2238	247.2238	247.2238	247.2238	0	0
NITROGEN	tons/hr	17.80807	17.80807	17.80807	17.80807	12.21167	1.087599	13.29927	13.29927	13.29927	13.29927	0	0
WATER	tons/hr	1.666142	1.666142	1.666142	1.666142	1.142537	0	1.142537	1.142537	1.142537	1.142537	5976.347	5976.347
Mass Fractions													
METHANE		0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0	0
CO2		0.993032	0.993032	0.993032	0.993032	0.993032	0	0.879132	0.879132	0.879132	0.879132	0	0
OXYGEN		5.35E-07	5.35E-07	5.35E-07	5.35E-07	5.35E-07	0.99562	0.114197	0.114197	0.114197	0.114197	0	0
NITROGEN		0.006372	0.006372	0.006372	0.006372	0.006372	0.00438	0.006143	0.006143	0.006143	0.006143	0	0
WATER		0.000596	0.000596	0.000596	0.000596	0.000596	0	0.000528	0.000528	0.000528	0.000528	1	1
Volume Flow	cuft/min	2220.921	1951.35	2093.071	9930.104	1522.97	850.5451	1992.8	1686.151	1926.823	8007.407	3342.014	3346.946
Vapor Phase													
Molar Enthalpy	Btu/lbmol				-154030		-275.923			-144457	-129382		
Mass Enthalpy	Btu/lb				-3515.64		-8.62828			-3437.1	-3078.42		
Molar Entropy	Btu/lbmol-R				2.005787		-9.83062			-12.1899	2.17983		
Mass Entropy	Btu/lb-R				0.045781		-0.30741			-0.29004	0.051865		
Molar Density	lbmol/cuft				0.214137		0.304308			0.891095	0.214424		
Mass Density	lb/cuft				9.381913		9.731419			37.45164	9.01199		
Enthalpy Flow	Btu/hr				-2E+10		-4284980			-1.5E+10	-1.3E+10		
Average MW					43.8127		31.97887			42.0288	42.0288		
Mole Flows	lbmol/hr				127584.1		15529.65			103018.9	103018.9		
Mass Flows	lb/hr				5589803		496620.6			4329761	4329761		
Volume Flow	cuft/hr				595806.2		51032.7			115609.4	480444.4		
Liquid Phase													
Molar Enthalpy	Btu/lbmol	-171471	-170877	-170417		-171471		-145664	-145003			-123919	-123859
Mass Enthalpy	Btu/lb	-3913.72	-3900.18	-3889.67		-3913.72		-3465.81	-3450.09			-6878.54	-6875.21
Molar Entropy	Btu/lbmol	-14.6295	-14.4727	-13.7305		-14.6295		-13.2824	-13.0763			-38.5367	-38.4423
Mass Entropy	Btu/lb-R	-0.33391	-0.33033	-0.31339		-0.33391		-0.31603	-0.31113			-2.13911	-2.13387
Molar Density	lbmol/cuft	0.957441	1.089708	1.015924		0.957441		0.861593	1.018285			3.30876	3.303884
Mass Density	lb/cuft	41.94808	47.74303	44.51037		41.94808		36.2117	42.79728			59.60824	59.5204
Enthalpy Flow	Btu/hr	-2.2E+10	-2.2E+10	-2.2E+10		-1.5E+10		-1.5E+10	-1.5E+10			-8.2E+10	-8.2E+10
Average MW		43.8127	43.8127	43.8127		43.8127		42.0288	42.0288			18.01528	18.01528
Mole Flows	lbmol/hr	127584.1	127584.1	127584.1		87489.24		103018.9	103018.9			663475.4	663475.4
Mass Flows	lb/hr	5589803	5589803	5589803		3833140		4329761	4329761			11952695	11952695
Volume Flow	cuft/hr	133255.3	117081	125584.3		91378.2		119568	101169.1			200520.8	200816.8

28.22. ASU Aspen Input



```
DYNAMICS
   DYNAMICS RESULTS=ON
IN-UNITS ENG SHORT-LENGTH=in
DEF-STREAMS CONVEN ALL
MODEL-OPTION
DATABANKS 'APV110 PURE37' / 'APV110 AQUEOUS' / 'APV110 SOLIDS' &
        / 'APV110 INORGANIC' / 'APESV110 AP-EOS' /  &
       'NISTV110 NIST-TRC' / NOASPENPCD
PROP-SOURCES 'APV110 PURE37' / 'APV110 AQUEOUS' /  &
       'APV110 SOLIDS' / 'APV110 INORGANIC' / 'APESV110 AP-EOS' &
        / 'NISTV110 NIST-TRC'
COMPONENTS
   NITROGEN N2 /
   OXYGEN O2 /
   WATER H2O /
   CO2
SOLVE
   RUN-MODE MODE=SIM
FLOWSHEET
   BLOCK LPC IN=212 211 208 OUT=213 215 214
   BLOCK HPC IN=209 210 OUT=211 212
```

```
  BLOCK AIRSPLIT IN=202 OUT=203 204 205
  BLOCK CRYO IN=213 214 216 203 204 206 OUT=207 218 217  &
    209 219 210
  BLOCK EXPANDER IN=207 OUT=208
  BLOCK MAC1 IN=201 OUT=201B
  BLOCK MAC2 IN=201D OUT=201E
  BLOCK MAC3 IN=201G OUT=201H
  BLOCK O2-PUMP IN=215 OUT=216
  BLOCK BAC1 IN=205 OUT=205B
  BLOCK BAC2 IN=205D OUT=205E
  BLOCK BAC3 IN=205G OUT=205H
  BLOCK BAC4 IN=205J OUT=205K
  BLOCK ALAM IN=201B 201E 205B 205E 205H 205K 317 201H  &
    323 OUT=318 201C 201F 201I 205C 205F 205I 205L 324
  BLOCK CW IN=CW-IN 201C 201F 201I 205C 205F 205I 205L  &
    OUT=201D 201G 202 205D 205G 205J 206 CW-OUT
PROPERTIES PENG-ROB
PROP-DATA PRKBV-1
  IN-UNITS ENG SHORT-LENGTH=in
  PROP-LIST PRKBV
  BPVAL NITROGEN OXYGEN -.0119000000 0.0 0.0 -459.6700000  &
    1340.330000
  BPVAL OXYGEN NITROGEN -.0119000000 0.0 0.0 -459.6700000  &
    1340.330000
  BPVAL NITROGEN CO2 -.0170000000 0.0 0.0 -459.6700000  &
    1340.330000
  BPVAL CO2 NITROGEN -.0170000000 0.0 0.0 -459.6700000  &
    1340.330000
  BPVAL WATER CO2 .1200000000 0.0 0.0 -459.6700000  &
    1340.330000
  BPVAL CO2 WATER .1200000000 0.0 0.0 -459.6700000  &
    1340.330000
```

```
STREAM 201
    SUBSTREAM MIXED TEMP=70. PRES=0. <psig>  &
        MOLE-FLOW=88404.36549
    MOLE-FRAC NITROGEN 0.79 / OXYGEN 0.21
STREAM 317
    SUBSTREAM MIXED TEMP=149.314 PRES=4341.4 <psig>  &
        MOLE-FLOW=127584.
    MOLE-FLOW NITROGEN 0.00996514 / WATER 0.00144979 / CO2  &
        0.988585
STREAM 323
    SUBSTREAM MIXED TEMP=143.585 PRES=4341.4 <psig>  &
        MOLE-FLOW=103019.
    MOLE-FLOW NITROGEN 0.00921666 / OXYGEN 0.14999302 / WATER  &
        0.00123124 / CO2 0.83956
STREAM CW-IN
    SUBSTREAM MIXED TEMP=90. PRES=0. <psig>  &
        VOLUME-FLOW=20000. <gal/min>
    MOLE-FRAC WATER 1.
BLOCK AIRSPLIT FSPLIT
    FRAC 203 0.1 / 205 0.53
BLOCK ALAM MHEATX
    HOT-SIDE IN=201B OUT=201C FREE-WATER=NO DPPARMOPT=NO
    HOT-SIDE IN=201E OUT=201F FREE-WATER=NO DPPARMOPT=NO
    HOT-SIDE IN=205B OUT=205C FREE-WATER=NO DPPARMOPT=NO
    HOT-SIDE IN=205E OUT=205F FREE-WATER=NO DPPARMOPT=NO
    HOT-SIDE IN=205H OUT=205I FREE-WATER=NO DPPARMOPT=NO
    HOT-SIDE IN=205K OUT=205L FREE-WATER=NO DPPARMOPT=NO
    COLD-SIDE IN=317 OUT=318 TEMP=170. FREE-WATER=NO  &
        DPPARMOPT=NO
    HOT-SIDE IN=201H OUT=201I FREE-WATER=NO DPPARMOPT=NO
    COLD-SIDE IN=323 OUT=324 TEMP=170. FREE-WATER=NO  &
        DPPARMOPT=NO
```

```
    PARAM NPOINT=50
BLOCK CRYO MHEATX
    COLD-SIDE IN=213 OUT=217 TEMP=90. FREE-WATER=NO  &
        DPPARMOPT=NO
    COLD-SIDE IN=214 OUT=218 TEMP=90. FREE-WATER=NO  &
        DPPARMOPT=NO
    COLD-SIDE IN=216 OUT=219 TEMP=90. PRES=1725.8 <psig>  &
        FREE-WATER=NO DPPARMOPT=NO
    HOT-SIDE IN=203 OUT=207 TEMP=-150. PRES=92. FREE-WATER=NO  &
        DPPARMOPT=NO
    HOT-SIDE IN=204 OUT=209 PRES=92. FREE-WATER=NO DPPARMOPT=NO
    HOT-SIDE IN=206 OUT=210 PRES=1050. FREE-WATER=NO  &
        DPPARMOPT=NO
    PARAM NPOINT=50
BLOCK CW MHEATX
    COLD-SIDE IN=CW-IN OUT=CW-OUT FREE-WATER=NO DPPARMOPT=NO
    HOT-SIDE IN=201C OUT=201D TEMP=100. PRES=26.9  &
        FREE-WATER=NO DPPARMOPT=NO
    HOT-SIDE IN=201F OUT=201G TEMP=100. PRES=50.6  &
        FREE-WATER=NO DPPARMOPT=NO
    HOT-SIDE IN=201I OUT=202 TEMP=100. PRES=97. FREE-WATER=NO  &
        DPPARMOPT=NO
    HOT-SIDE IN=205C OUT=205D TEMP=100. PRES=173.5  &
        FREE-WATER=NO DPPARMOPT=NO
    HOT-SIDE IN=205F OUT=205G TEMP=100. PRES=314.2  &
        FREE-WATER=NO DPPARMOPT=NO
    HOT-SIDE IN=205I OUT=205J TEMP=100. PRES=573.1  &
        FREE-WATER=NO DPPARMOPT=NO
    HOT-SIDE IN=205L OUT=206 TEMP=100. PRES=1050.  &
        FREE-WATER=NO DPPARMOPT=NO
BLOCK HPC RADFRAC
    SUBOBJECTS INTERNALS = CS-1
```

```
    PARAM NSTAGE=14 ALGORITHM=STANDARD HYDRAULIC=NO MAXOL=25  &
        DAMPING=NONE
    PARAM2 STATIC-DP=YES
    COL-CONFIG CONDENSER=TOTAL REBOILER=NONE CA-CONFIG=INT-1
    FEEDS 209 14 ON-STAGE / 210 14 ON-STAGE
    PRODUCTS 212 14 L / 211 1 L
    P-SPEC 1 80.
    COL-SPECS DP-COL=5. MOLE-RR=1.1
    SC-REFLUX OPTION=0
    REPORT NOHYDRAULIC
    INTERNALS CS-1 STAGE1=2 STAGE2=14 INTERNAL=PACKING  &
        P-UPDATE=NO PACKTYPE=FLEXIPAC PACK-MAT=METAL  &
        PACK-SIZE="4Y" PACK-HT=130. <in> DPMETH=WALLIS
    PACK-SIZE 1 2 14 FLEXIPAC
BLOCK LPC RADFRAC
    SUBOBJECTS INTERNALS = CS-1
    PARAM NSTAGE=39 ALGORITHM=STANDARD HYDRAULIC=NO MAXOL=25  &
        DAMPING=NONE
    PARAM2 STATIC-DP=YES
    COL-CONFIG CONDENSER=NONE CA-CONFIG=INT-1
    FEEDS 212 25 ON-STAGE / 211 1 ON-STAGE / 208 15  &
        ON-STAGE
    PRODUCTS 213 1 V / 214 13 V MOLE-FLOW=15145.54634 /  &
        215 39 L
    P-SPEC 1 8.3 <psig>
    COL-SPECS DP-COL=5. MOLE-BR=2.5
    REPORT NOHYDRAULIC
    INTERNALS CS-1 STAGE1=1 STAGE2=38 INTERNAL=PACKING  &
        P-UPDATE=NO PACKTYPE=FLEXIPAC PACK-MAT=METAL  &
        PACK-SIZE="4Y" PACK-HT=380. <in> DPMETH=WALLIS
    PACK-SIZE 1 1 38 FLEXIPAC
BLOCK O2-PUMP PUMP
```

```
   PARAM PRES=1730.8 <psig> EFF=0.85
BLOCK BAC1 COMPR
   PARAM TYPE=ASME-POLYTROP PRATIO=1.84 PEFF=0.85 SB-MAXIT=30  &
      SB-TOL=0.0001
BLOCK BAC2 COMPR
   PARAM TYPE=ASME-POLYTROP PRATIO=1.84 PEFF=0.85 SB-MAXIT=30  &
      SB-TOL=0.0001
BLOCK BAC3 COMPR
   PARAM TYPE=ASME-POLYTROP PRATIO=1.84 PEFF=0.85 SB-MAXIT=30  &
      SB-TOL=0.0001
BLOCK BAC4 COMPR
   PARAM TYPE=ASME-POLYTROP PRES=1055. PEFF=0.85 SB-MAXIT=30  &
     SB-TOL=0.0001
BLOCK EXPANDER COMPR
   PARAM TYPE=ASME-POLYTROP PRES=10.5 <psig> PEFF=0.85 MEFF=1.  &
      SB-MAXIT=30 SB-TOL=0.0001 MODEL-TYPE=TURBINE
BLOCK MAC1 COMPR
   PARAM TYPE=ASME-POLYTROP PRATIO=1.96 PEFF=0.85 SB-MAXIT=30  &
      SB-TOL=0.0001
BLOCK MAC2 COMPR
   PARAM TYPE=ASME-POLYTROP PRATIO=1.96 PEFF=0.85 SB-MAXIT=30  &
      SB-TOL=0.0001
BLOCK MAC3 COMPR
   PARAM TYPE=ASME-POLYTROP PRES=97. PEFF=0.85 SB-MAXIT=30  &
      SB-TOL=0.0001
DESIGN-SPEC O2PURITY
   DEFINE O2PUR MOLE-FRAC STREAM=216 SUBSTREAM=MIXED  &
      COMPONENT=OXYGEN
   SPEC "O2PUR" TO "0.995"
   TOL-SPEC ".00001"
   VARY BLOCK-VAR BLOCK=LPC VARIABLE=MOLE-BR SENTENCE=COL-SPECS
   LIMITS "2" "4"
```

EO-CONV-OPTI

STREAM-REPOR MOLEFLOW

PROPERTY-REP PCES

28.23. ASU Full Aspen Stream Report

All stream numbers match number in report. Streams with letter (B, C, D, ...) indicate intermediate stream for intercooling. CW-In & CW-Out is cw for MAC and BAC intercoolers. 317, 318, 323, 324 are from Allam Cycle heat integration.

	Units	201	201B	201C	201D	201E	201F	201G	201H	201I	202	203
Description												
From			MAC1	ALAM	CW	MAC2	ALAM	CW	MAC3	ALAM	CW	AIRSPLIT
To		MAC1	ALAM	CW	MAC2	ALAM	CW	MAC3	ALAM	CW	AIRSPLIT	CRYO
Stream Class		CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN
Maximum Relative Error												
Cost Flow	$/hr											
MIXED Substream												
Phase		Vapor Pha	Vapor Pha	Vapor Pha	Vapor Pha	Vapor Pha	Vapor Pha	Vapor Pha	Vapor Pha	Vapor Pha	Vapor Pha	Vapor Pha
Temperature	F	70	203.8258	191.7468	100	241.205	191.7468	100	236.1229	191.7468	100	100
Pressure	psig	-1.78E-15	14.10811	14.10811	12.20405	38.02805	38.02805	35.90405	82.30405	82.30405	82.30405	82.30405
Molar Vapor Fraction		1	1	1	1	1	1	1	1	1	1	1
Molar Liquid Fraction		0	0	0	0	0	0	0	0	0	0	0
Molar Solid Fraction		0	0	0	0	0	0	0	0	0	0	0
Mass Vapor Fraction		1	1	1	1	1	1	1	1	1	1	1
Mass Liquid Fraction		0	0	0	0	0	0	0	0	0	0	0
Mass Solid Fraction		0	0	0	0	0	0	0	0	0	0	0
Molar Enthalpy	Btu/lbmol	-52.3656	881.4048	796.6402	154.4349	1140.967	792.9485	149.2865	1099.432	786.1718	139.2792	139.2792
Mass Enthalpy	Btu/lb	-1.81507	30.55087	27.6128	5.352957	39.54771	27.48484	5.174504	38.10802	27.24995	4.827635	4.827635
Molar Entropy	Btu/lbmol	0.923542	1.159289	1.030357	0.103577	0.33927	-0.17566	-1.15902	-0.93116	-1.39637	-2.4667	-2.4667
Mass Entropy	Btu/lb-R	0.032011	0.040183	0.035714	0.00359	0.01176	-0.00609	-0.04017	-0.03228	-0.0484	-0.0855	-0.0855
Molar Density	lbmol/cuft	0.002587	0.004046	0.004121	0.004482	0.007009	0.007544	0.008437	0.012987	0.013881	0.016193	0.016193
Mass Density	lb/cuft	0.074635	0.116718	0.118889	0.129313	0.2022	0.21764	0.243399	0.374671	0.400464	0.467164	0.467164
Enthalpy Flow	Btu/hr	-4629344	77920033	70426468	13652723	1.01E+08	70100105	13197579	97194551	69501015	12312887	1231289
Average MW		28.8504	28.8504	28.8504	28.8504	28.8504	28.8504	28.8504	28.8504	28.8504	28.8504	28.8504
Mole Flows	lbmol/hr	88404.37	88404.37	88404.37	88404.37	88404.37	88404.37	88404.37	88404.37	88404.37	88404.37	8840.437
NITROGEN	lbmol/hr	69839.45	69839.45	69839.45	69839.45	69839.45	69839.45	69839.45	69839.45	69839.45	69839.45	6983.945
OXYGEN	lbmol/hr	18564.92	18564.92	18564.92	18564.92	18564.92	18564.92	18564.92	18564.92	18564.92	18564.92	1856.492
WATER	lbmol/hr	0	0	0	0	0	0	0	0	0	0	0
CO2	lbmol/hr	0	0	0	0	0	0	0	0	0	0	0
Mole Fractions												
NITROGEN		0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79
OXYGEN		0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21
WATER		0	0	0	0	0	0	0	0	0	0	0
CO2		0	0	0	0	0	0	0	0	0	0	0
Mass Flows	tons/hr	1275.251	1275.251	1275.251	1275.251	1275.251	1275.251	1275.251	1275.251	1275.251	1275.251	127.5251
NITROGEN	tons/hr	978.223	978.223	978.223	978.223	978.223	978.223	978.223	978.223	978.223	978.223	97.8223
OXYGEN	tons/hr	297.0275	297.0275	297.0275	297.0275	297.0275	297.0275	297.0275	297.0275	297.0275	297.0275	29.70275
WATER	tons/hr	0	0	0	0	0	0	0	0	0	0	0
CO2	tons/hr	0	0	0	0	0	0	0	0	0	0	0
Mass Fractions												
NITROGEN		0.767083	0.767083	0.767083	0.767083	0.767083	0.767083	0.767083	0.767083	0.767083	0.767083	0.767083
OXYGEN		0.232917	0.232917	0.232917	0.232917	0.232917	0.232917	0.232917	0.232917	0.232917	0.232917	0.232917
WATER		0	0	0	0	0	0	0	0	0	0	0
CO2		0	0	0	0	0	0	0	0	0	0	0
Volume Flow	cuft/min	569550.8	364197.3	357545	328725.2	210229.7	195315.4	174644.5	113455.1	106147.9	90992.39	9099.239
Vapor Phase												
Molar Enthalpy	Btu/lbmol	-52.3656	881.4048	796.6402	154.4349	1140.967	792.9485	149.2865	1099.432	786.1718	139.2792	139.2792
Mass Enthalpy	Btu/lb	-1.81507	30.55087	27.6128	5.352957	39.54771	27.48484	5.174504	38.10802	27.24995	4.827635	4.827635
Molar Entropy	Btu/lbmol	0.923542	1.159289	1.030357	0.103577	0.33927	-0.17566	-1.15902	-0.93116	-1.39637	-2.4667	-2.4667
Mass Entropy	Btu/lb-R	0.032011	0.040183	0.035714	0.00359	0.01176	-0.00609	-0.04017	-0.03228	-0.0484	-0.0855	-0.0855
Molar Density	lbmol/cuft	0.002587	0.004046	0.004121	0.004482	0.007009	0.007544	0.008437	0.012987	0.013881	0.016193	0.016193
Mass Density	lb/cuft	0.074635	0.116718	0.118889	0.129313	0.2022	0.21764	0.243399	0.374671	0.400464	0.467164	0.467164
Enthalpy Flow	Btu/hr	-4629344	77920032	70426468	13652723	1.01E+08	70100105	13197579	97194551	69501015	12312887	1231289
Average MW		28.8504	28.8504	28.8504	28.8504	28.8504	28.8504	28.8504	28.8504	28.8504	28.8504	28.8504
Mole Flows	lbmol/hr	88404.37	88404.37	88404.37	88404.37	88404.37	88404.37	88404.37	88404.37	88404.37	88404.37	8840.437
NITROGEN	lbmol/hr	69839.45	69839.45	69839.45	69839.45	69839.45	69839.45	69839.45	69839.45	69839.45	69839.45	6983.945
OXYGEN	lbmol/hr	18564.92	18564.92	18564.92	18564.92	18564.92	18564.92	18564.92	18564.92	18564.92	18564.92	1856.492
WATER	lbmol/hr	0	0	0	0	0	0	0	0	0	0	0
CO2	lbmol/hr	0	0	0	0	0	0	0	0	0	0	0
Mass Flows	lb/hr	2550501	2550501	2550501	2550501	2550501	2550501	2550501	2550501	2550501	2550501	255050.1
Volume Flow	cuft/hr	34173051	21851835	21452702	19723513	12613779	11718923	10478669	6807306	6368871	5459543	545954.3

	Units	204	205	205B	205C	205D	205E	205F	205G	205H	205I	205J
Description												
From		AIRSPLIT	AIRSPLIT	BAC1	ALAM	CW	BAC2	ALAM	CW	BAC3	ALAM	CW
To		CRYO	BAC1	ALAM	CW	BAC2	ALAM	CW	BAC3	ALAM	CW	BAC4
Stream Class		CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN
Maximum Relative Error												
Cost Flow	$/hr											
MIXED Substream												
Phase		Vapor Pha	Vapor Pha	Vapor Pha	Vapor Pha	Vapor Pha	Vapor Pha	Vapor Pha	Vapor Pha	Vapor Pha	Vapor Pha	Vapor Pha
Temperature	F	100	100	226.807	191.7468	100	226.9902	191.7468	100	227.2291	191.7468	100
Pressure	psig	82.30405	82.30405	163.7841	163.7841	158.8041	304.5441	304.5441	299.5041	563.4321	563.4321	558.4041
Molar Vapor Fraction		1	1	1	1	1	1	1	1	1	1	1
Molar Liquid Fraction		0	0	0	0	0	0	0	0	0	0	0
Molar Solid Fraction		0	0	0	0	0	0	0	0	0	0	0
Mass Vapor Fraction		1	1	1	1	1	1	1	1	1	1	1
Mass Liquid Fraction		0	0	0	0	0	0	0	0	0	0	0
Mass Solid Fraction		0	0	0	0	0	0	0	0	0	0	0
Molar Enthalpy	Btu/lbmol	139.2792	139.2792	1022.87	773.8929	122.9912	1006.13	753.2662	93.73142	976.4389	717.2535	42.30902
Mass Enthalpy	Btu/lb	4.827635	4.827635	35.45428	26.82434	4.263066	34.87405	26.10939	3.248878	33.8449	24.86113	1.466497
Molar Entropy	Btu/lbmol	-2.4667	-2.4667	-2.25331	-2.62559	-3.6465	-3.43325	-3.81129	-4.87114	-4.6581	-5.04553	-6.14523
Mass Entropy	Btu/lb-R	-0.0855	-0.0855	-0.0781	-0.09101	-0.12639	-0.119	-0.13211	-0.16884	-0.16146	-0.17489	-0.213
Molar Density	lbmol/cuft	0.016193	0.016193	0.024216	0.025545	0.029018	0.043273	0.045693	0.052709	0.078183	0.082681	0.096544
Mass Density	lb/cuft	0.467164	0.467164	0.698652	0.73698	0.837168	1.248455	1.318248	1.520677	2.255618	2.385376	2.785322
Enthalpy Flow	Btu/hr	4555768	6525830	47925868	36260221	5762666	47141544	35293771	4391721	45750373	33606420	1982360
Average MW		28.8504	28.8504	28.8504	28.8504	28.8504	28.8504	28.8504	28.8504	28.8504	28.8504	28.8504
Mole Flows	lbmol/hr	32709.62	46854.31	46854.31	46854.31	46854.31	46854.31	46854.31	46854.31	46854.31	46854.31	46854.31
NITROGEN	lbmol/hr	25840.6	37014.91	37014.91	37014.91	37014.91	37014.91	37014.91	37014.91	37014.91	37014.91	37014.91
OXYGEN	lbmol/hr	6869.019	9839.406	9839.406	9839.406	9839.406	9839.406	9839.406	9839.406	9839.406	9839.406	9839.406
WATER	lbmol/hr	0	0	0	0	0	0	0	0	0	0	0
CO2	lbmol/hr	0	0	0	0	0	0	0	0	0	0	0
Mole Fractions												
NITROGEN		0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79
OXYGEN		0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21
WATER		0	0	0	0	0	0	0	0	0	0	0
CO2		0	0	0	0	0	0	0	0	0	0	0
Mass Flows	tons/hr	471.8427	675.8828	675.8828	675.8828	675.8828	675.8828	675.8828	675.8828	675.8828	675.8828	675.8828
NITROGEN	tons/hr	361.9425	518.4582	518.4582	518.4582	518.4582	518.4582	518.4582	518.4582	518.4582	518.4582	518.4582
OXYGEN	tons/hr	109.9002	157.4246	157.4246	157.4246	157.4246	157.4246	157.4246	157.4246	157.4246	157.4246	157.4246
WATER	tons/hr	0	0	0	0	0	0	0	0	0	0	0
CO2	tons/hr	0	0	0	0	0	0	0	0	0	0	0
Mass Fractions												
NITROGEN		0.767083	0.767083	0.767083	0.767083	0.767083	0.767083	0.767083	0.767083	0.767083	0.767083	0.767083
OXYGEN		0.232917	0.232917	0.232917	0.232917	0.232917	0.232917	0.232917	0.232917	0.232917	0.232917	0.232917
WATER		0	0	0	0	0	0	0	0	0	0	0
CO2		0	0	0	0	0	0	0	0	0	0	0
Volume Flow	cuft/min	33667.18	48225.97	32247	30569.91	26911.49	18045.85	17090.43	14815.39	9988.141	9444.812	8088.626
Vapor Phase												
Molar Enthalpy	Btu/lbmol	139.2792	139.2792	1022.87	773.8929	122.9912	1006.13	753.2662	93.73142	976.4389	717.2535	42.30902
Mass Enthalpy	Btu/lb	4.827635	4.827635	35.45427	26.82434	4.263066	34.87405	26.10939	3.248878	33.8449	24.86113	1.466497
Molar Entropy	Btu/lbmol	-2.4667	-2.4667	-2.25331	-2.62559	-3.6465	-3.43325	-3.81129	-4.87114	-4.6581	-5.04553	-6.14523
Mass Entropy	Btu/lb-R	-0.0855	-0.0855	-0.0781	-0.09101	-0.12639	-0.119	-0.13211	-0.16884	-0.16146	-0.17489	-0.213
Molar Density	lbmol/cuft	0.016193	0.016193	0.024216	0.025545	0.029018	0.043273	0.045693	0.052709	0.078183	0.082681	0.096544
Mass Density	lb/cuft	0.467164	0.467164	0.698652	0.73698	0.837168	1.248455	1.318248	1.520677	2.255618	2.385376	2.785322
Enthalpy Flow	Btu/hr	4555768	6525830	47925868	36260221	5762666	47141544	35293771	4391721	45750374	33606420	1982360
Average MW		28.8504	28.8504	28.8504	28.8504	28.8504	28.8504	28.8504	28.8504	28.8504	28.8504	28.8504
Mole Flows	lbmol/hr	32709.62	46854.31	46854.31	46854.31	46854.31	46854.31	46854.31	46854.31	46854.31	46854.31	46854.31
NITROGEN	lbmol/hr	25840.6	37014.91	37014.91	37014.91	37014.91	37014.91	37014.91	37014.91	37014.91	37014.91	37014.91
OXYGEN	lbmol/hr	6869.019	9839.406	9839.406	9839.406	9839.406	9839.406	9839.406	9839.406	9839.406	9839.406	9839.406
WATER	lbmol/hr	0	0	0	0	0	0	0	0	0	0	0
CO2	lbmol/hr	0	0	0	0	0	0	0	0	0	0	0
Mass Flows	lb/hr	943685.4	1351766	1351766	1351766	1351766	1351766	1351766	1351766	1351766	1351766	1351766
Volume Flow	cuft/hr	2020031	2893558	1934820	1834195	1614689	1082751	1025426	888923.4	599288.5	566688.7	485317.6

	Units	205K	205L	206	207	208	209	210	211	212	213	214
Description												
From		BAC4	ALAM	CW	CRYO	EXPANDEF	CRYO	CRYO	HPC	HPC	LPC	LPC
To		ALAM	CW	CRYO	EXPANDEF	LPC	HPC	HPC	LPC	LPC	CRYO	CRYO
Stream Class		CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN
Maximum Relative Error												
Cost Flow	$/hr											
MIXED Substream												
Phase		Vapor Pha	Vapor Pha	Vapor Pha	Vapor Pha	Vapor Pha	Vapor Pha	Liquid Pha	Liquid Pha	Liquid Pha	Vapor Pha	Vapor Pha
Temperature	F	227.5144	191.7468	100	-150	-235.643	-234.282	-234.282	-287.784	-280.851	-312.545	-305.749
Pressure	psig	1040.304	1040.304	1035.304	77.30405	10.5	77.30405	1035.304	65.30405	70.30405	8.3	9.878947
Molar Vapor Fraction		1	1	1	1	1	1	0	0	0	1	1
Molar Liquid Fraction		0	0	0	0	0	0	1	1	1	0	0
Molar Solid Fraction		0	0	0	0	0	0	0	0	0	0	0
Mass Vapor Fraction		1	1	1	1	1	1	0	0	0	1	1
Mass Liquid Fraction		0	0	0	0	0	0	1	1	1	0	0
Mass Solid Fraction		0	0	0	0	0	0	0	0	0	0	0
Molar Enthalpy	Btu/lbmol	926.477	657.3139	-43.9923	-1636.64	-2199.69	-2260.35	-4047.56	-4743.99	-4844.61	-2749.56	-2703.48
Mass Enthalpy	Btu/lb	32.11315	22.78353	-1.52484	-56.7285	-76.2446	-78.3474	-140.295	-169.056	-165.567	-98.0094	-94.271
Molar Entropy	Btu/lbmol	-5.93197	-6.33423	-7.48562	-6.57237	-6.19633	-8.92646	-19.5771	-23.7196	-22.6492	-9.9427	-8.97486
Mass Entropy	Btu/lb-R	-0.20561	-0.21955	-0.25946	-0.22781	-0.21477	-0.30941	-0.67857	-0.84527	-0.77405	-0.35441	-0.31296
Molar Density	lbmol/cuft	0.141777	0.150252	0.177427	0.028547	0.010706	0.041258	1.204369	1.600453	1.709546	0.015446	0.015748
Mass Density	lb/cuft	4.090314	4.334842	5.118835	0.823599	0.308866	1.190304	34.74653	44.91132	50.02245	0.433315	0.451615
Enthalpy Flow	Btu/hr	43409444	30797992	-2061227	-1.4E+07	-1.9E+07	-7.4E+07	-1.9E+08	-1.3E+08	-2.5E+08	-1.6E+08	-4.1E+07
Average MW		28.8504	28.8504	28.8504	28.8504	28.8504	28.8504	28.8504	28.06162	29.26066	28.0541	28.67776
Mole Flows	lbmol/hr	46854.31	46854.31	46854.31	8840.437	8840.437	32709.62	46854.31	27223.76	52340.17	57729.17	15145.55
NITROGEN	lbmol/hr	37014.91	37014.91	37014.91	6983.945	6983.945	25840.6	37014.91	26894.88	35960.62	57140.78	12621.08
OXYGEN	lbmol/hr	9839.406	9839.406	9839.406	1856.492	1856.492	6869.019	9839.406	328.8734	16379.55	588.3936	2524.467
WATER	lbmol/hr	0	0	0	0	0	0	0	0	0	0	0
CO2	lbmol/hr	0	0	0	0	0	0	0	0	0	0	0
Mole Fractions												
NITROGEN		0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.98792	0.687056	0.989808	0.83332
OXYGEN		0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.01208	0.312944	0.010192	0.16668
WATER		0	0	0	0	0	0	0	0	0	0	0
CO2		0	0	0	0	0	0	0	0	0	0	0
Mass Flows	tons/hr	675.8828	675.8828	675.8828	127.5251	127.5251	471.8427	675.8828	381.9714	765.754	809.77	217.1701
NITROGEN	tons/hr	518.4582	518.4582	518.4582	97.8223	97.8223	361.9425	518.4582	376.7097	503.691	800.356	176.7802
OXYGEN	tons/hr	157.4246	157.4246	157.4246	29.70275	29.70275	109.9002	157.4246	5.261777	262.063	9.413945	40.38996
WATER	tons/hr	0	0	0	0	0	0	0	0	0	0	0
CO2	tons/hr	0	0	0	0	0	0	0	0	0	0	0
Mass Fractions												
NITROGEN		0.767083	0.767083	0.767083	0.767083	0.767083	0.767083	0.767083	0.986225	0.657771	0.988375	0.814017
OXYGEN		0.232917	0.232917	0.232917	0.232917	0.232917	0.232917	0.232917	0.013775	0.342229	0.011625	0.185983
WATER		0	0	0	0	0	0	0	0	0	0	0
CO2		0	0	0	0	0	0	0	0	0	0	0
Volume Flow	cuft/min	5507.994	5197.288	4401.28	5161.292	13762.71	13213.5	648.3935	283.5005	510.2735	62292.64	16029.15
Vapor Phase												
Molar Enthalpy	Btu/lbmol	926.4771	657.3139	-43.9923	-1636.64	-2199.69	-2260.35				-2749.56	-2703.48
Mass Enthalpy	Btu/lb	32.11315	22.78353	-1.52484	-56.7285	-76.2446	-78.3474				-98.0094	-94.271
Molar Entropy	Btu/lbmol	-5.93197	-6.33423	-7.48562	-6.57237	-6.19633	-8.92646				-9.9427	-8.97486
Mass Entropy	Btu/lb-R	-0.20561	-0.21955	-0.25946	-0.22781	-0.21477	-0.30941				-0.35441	-0.31296
Molar Density	lbmol/cuft	0.141777	0.150252	0.177427	0.028547	0.010706	0.041258				0.015446	0.015748
Mass Density	lb/cuft	4.090314	4.334842	5.118835	0.823599	0.308866	1.190304				0.433315	0.451615
Enthalpy Flow	Btu/hr	43409447	30797992	-2061227	-1.4E+07	-1.9E+07	-7.4E+07				-1.6E+08	-4.1E+07
Average MW		28.8504	28.8504	28.8504	28.8504	28.8504	28.8504				28.0541	28.67776
Mole Flows	lbmol/hr	46854.31	46854.31	46854.31	8840.437	8840.437	32709.62				57729.17	15145.55
NITROGEN	lbmol/hr	37014.91	37014.91	37014.91	6983.945	6983.945	25840.6				57140.78	12621.08
OXYGEN	lbmol/hr	9839.406	9839.406	9839.406	1856.492	1856.492	6869.019				588.3936	2524.467
WATER	lbmol/hr	0	0	0	0	0	0				0	0
CO2	lbmol/hr	0	0	0	0	0	0				0	0
Mass Flows	lb/hr	1351766	1351766	1351766	255050.1	255050.1	943685.4				1619540	434340.3
Volume Flow	cuft/hr	330479.7	311837.3	264076.8	309677.5	825762.5	792810.1				3737558	961748.7
Liquid Phase												
Average MW								28.8504	28.06162	29.26066		
Mole Flows	lbmol/hr							46617.77	27086.32	52075.94		
Mass Flows	tons/hr							672.4706	380.0431	761.8882		
Volume Flow	cuft/hr							38707.21	16924.15	30461.85		

	Units	215	216	217	218	219	317	318	323	324	CW-IN	CW-OUT
Description												
From		LPC	O2-PUMP	CRYO	CRYO	CRYO		ALAM		ALAM		CW
To		O2-PUMP	CRYO				ALAM		ALAM		CW	
Stream Class		CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN	CONVEN
Maximum Relative Error												
Cost Flow	$/hr											
MIXED Substream												
Phase		Liquid Pha	Liquid Pha	Vapor Pha	Vapor Pha	Vapor Pha	Vapor Pha	Vapor Pha	Vapor Pha	Vapor Pha	Liquid Pha	Liquid Pha
Temperature	F	-285.947	-277.531	90	90	90	149.314	170	143.585	170	90	117.7874
Pressure	psig	13.3	1730.8	8.3	9.878947	1725.8	4341.4	4341.4	4341.4	4341.4	-1.78E-15	-1.78E-15
Molar Vapor Fraction		0	0	1	1	1	1	1	1	1	0	0
Molar Liquid Fraction		1	1	0	0	0	0	0	0	0	1	1
Molar Solid Fraction		0	0	0	0	0	0	0	0	0	0	0
Mass Vapor Fraction		0	0	1	1	1	1	1	1	1	0	0
Mass Liquid Fraction		1	1	0	0	0	0	0	0	0	1	1
Mass Solid Fraction		0	0	0	0	0	0	0	0	0	0	0
Molar Enthalpy	Btu/lbmol	-5385.96	-5212.82	85.50082	85.05293	-325.526	-170927	-170469	-145063	-144522	-123454	-122913
Mass Enthalpy	Btu/lb	-168.422	-163.008	3.047712	2.965815	-10.1794	-3901.32	-3890.85	-3451.51	-3438.64	-6852.71	-6822.69
Molar Entropy	Btu/lbmol	-25.4153	-25.1698	-0.61753	0.03195	-9.84515	-14.3918	-13.6513	-13.0061	-12.1286	-39.654	-38.6941
Mass Entropy	Btu/lb-R	-0.79475	-0.78708	-0.02201	0.001114	-0.30786	-0.32848	-0.31158	-0.30946	-0.28858	-2.20113	-2.14785
Molar Density	lbmol/cuft	2.159642	2.112047	0.003901	0.004169	0.315108	1.134552	1.055362	1.064184	0.965028	3.420101	3.367636
Mass Density	lb/cuft	69.06295	67.54093	0.10943	0.119564	10.07681	49.70778	46.23826	44.72636	40.55898	61.61408	60.66891
Enthalpy Flow	Btu/hr	-8.4E+07	-8.1E+07	4935891	1288173	-5055300	-2.2E+10	-2.2E+10	-1.5E+10	-1.5E+10	-6.8E+10	-6.7E+10
Average MW		31.97889	31.97889	28.0541	28.67776	31.97889	43.81271	43.81271	42.0288	42.0288	18.01528	18.01528
Mole Flows	lbmol/hr	15529.65	15529.65	57729.17	15145.55	15529.65	127584	127584	103019	103019	548641.3	548641.3
NITROGEN	lbmol/hr	77.59031	77.59031	57140.78	12621.08	77.59031	1271.393	1271.393	949.4902	949.4902	0	0
OXYGEN	lbmol/hr	15452.06	15452.06	588.3936	2524.467	15452.06	0	0	15452.12	15452.12	0	0
WATER	lbmol/hr	0	0	0	0	0	184.97	184.97	126.841	126.841	548641.3	548641.3
CO2	lbmol/hr	0	0	0	0	0	126127.6	126127.6	86490.55	86490.55	0	0
Mole Fractions												
NITROGEN		0.004996	0.004996	0.989808	0.83332	0.004996	0.009965	0.009965	0.009217	0.009217	0	0
OXYGEN		0.995004	0.995004	0.010192	0.16668	0.995004	0	0	0.149993	0.149993	0	0
WATER		0	0	0	0	0	0.00145	0.00145	0.001231	0.001231	1	1
CO2		0	0	0	0	0	0.988585	0.988585	0.839559	0.839559	0	0
Mass Flows	tons/hr	248.3104	248.3104	809.77	217.1701	248.3104	2794.9	2794.9	2164.882	2164.882	4941.963	4941.963
NITROGEN	tons/hr	1.086787	1.086787	800.356	176.7802	1.086787	17.80806	17.80806	13.29926	13.29926	0	0
OXYGEN	tons/hr	247.2237	247.2237	9.413945	40.38996	247.2237	0	0	247.2246	247.2246	0	0
WATER	tons/hr	0	0	0	0	0	1.666143	1.666143	1.142538	1.142538	4941.963	4941.963
CO2	tons/hr	0	0	0	0	0	2775.426	2775.426	1903.216	1903.216	0	0
Mass Fractions												
NITROGEN		0.004377	0.004377	0.988375	0.814017	0.004377	0.006372	0.006372	0.006143	0.006143	0	0
OXYGEN		0.995623	0.995623	0.011625	0.185983	0.995623	0	0	0.114198	0.114198	0	0
WATER		0	0	0	0	0	0.000596	0.000596	0.000528	0.000528	1	1
CO2		0	0	0	0	0	0.993032	0.993032	0.879131	0.879131	0	0
Volume Flow	cuft/min	119.8474	122.5481	246663.4	60545.19	821.3922	1874.221	2014.854	1613.428	1779.205	2673.611	2715.264
Vapor Phase												
Molar Enthalpy	Btu/lbmol			85.50082	85.05293	-325.526	-170927	-170469	-145063	-144522		
Mass Enthalpy	Btu/lb			3.047712	2.965815	-10.1794	-3901.32	-3890.85	-3451.51	-3438.64		
Molar Entropy	Btu/lbmol-R			-0.61753	0.03195	-9.84515	-14.3918	-13.6513	-13.0061	-12.1286		
Mass Entropy	Btu/lb-R			-0.02201	0.001114	-0.30786	-0.32848	-0.31158	-0.30946	-0.28858		
Molar Density	lbmol/cuft			0.003901	0.004169	0.315108	1.134552	1.055362	1.064184	0.965028		
Mass Density	lb/cuft			0.10943	0.119564	10.07681	49.70778	46.23826	44.72636	40.55898		
Enthalpy Flow	Btu/hr			4935891	1288173	-5055300	-2.2E+10	-2.2E+10	-1.5E+10	-1.5E+10		
Average MW				28.0541	28.67776	31.97889	43.81271	43.81271	42.0288	42.0288		
Mole Flows	lbmol/hr			57729.17	15145.55	15529.65	127584	127584	103019	103019		
NITROGEN	lbmol/hr			57140.78	12621.08	77.59031	1271.393	1271.393	949.4902	949.4902		
OXYGEN	lbmol/hr			588.3936	2524.467	15452.06	0	0	15452.12	15452.12		
WATER	lbmol/hr			0	0	0	184.97	184.97	126.841	126.841		
CO2	lbmol/hr			0	0	0	126127.6	126127.6	86490.55	86490.55		
Mass Flows	lb/hr			1619540	434340.3	496620.9	5589801	5589801	4329765	4329765		
Volume Flow	cuft/hr			14799801	3632712	49283.53	112453.2	120891.2	96805.66	106752.3		
Liquid Phase												
Average MW		31.97889	31.97889								18.01528	18.01528
Mole Flows	lbmol/hr	15451.25	15451.25								548641.3	548641.3
Mass Flows	tons/hr	247.0569	247.0569								4941.963	4941.963
Volume Flow	cuft/hr	7154.541	7315.767								160416.7	162613.2

28.24. Cash Flow Tables Under Current Tax Code

Under current code, the CO_2 credit is $43.33 in 2024, $46.67 in 2025, $50 from 2026-2035, and $0 from 2036-2043.

Year	Percentage of Design Capacity	Electricity Price ($/MW-hr)	Sales	Capital Costs	Working Capital	Var Costs	Fixed Costs	Total Costs	15 Year MACRS	Depreciation	Taxible Income	Taxes	CO2 Credit ($/tonne CO2)	CO2 Credit	Net Earnings	Cash Flow	Cumulative Net Present Value
2022	0%	$60.00	-	-	-	-	-	-		-	-	-	$ -	-	-	-	-
2023	0%	$60.00	-	(793,623,891)	(8,373,971)	-	-	-		-	-	-	$ -	-	-	(801,997,862)	(697,389,445)
2024	45%	$60.00	64,144,224	-	(4,186,985)	(39,994,784)	(81,057,391)	(121,052,175)	5.00%	(35,429,638)	(92,337,589)	21,237,645	$ 43	21,926,135	(49,173,808)	(17,931,156)	(710,947,975)
2025	68%	$60.00	96,216,336	-	(4,186,985)	(59,992,176)	(81,057,391)	(141,049,567)	9.50%	(67,316,312)	(112,149,543)	25,794,395	$ 47	35,424,396	(50,930,752)	12,198,575	(702,927,214)
2026	90%	$60.00	128,288,448	-	-	(79,989,568)	(81,057,391)	(161,046,959)	8.55%	(60,584,681)	(93,343,192)	21,468,934	$ 50	50,602,666	(21,271,592)	39,313,089	(680,449,828)
2027	90%	$60.00	128,288,448	-	-	(79,989,568)	(81,057,391)	(161,046,959)	7.70%	(54,561,643)	(87,320,153)	20,083,635	$ 50	50,602,666	(16,633,852)	37,927,790	(661,593,013)
2028	90%	$60.00	128,288,448	-	-	(79,989,568)	(81,057,391)	(161,046,959)	6.93%	(49,105,478)	(81,863,989)	18,828,717	$ 50	50,602,666	(12,432,606)	36,672,872	(645,738,318)
2029	90%	$60.00	128,288,448	-	-	(79,989,568)	(81,057,391)	(161,046,959)	6.23%	(44,145,329)	(76,903,840)	17,687,883	$ 50	50,602,666	(8,613,291)	35,532,038	(632,380,509)
2030	90%	$60.00	128,288,448	-	-	(79,989,568)	(81,057,391)	(161,046,959)	5.90%	(41,806,973)	(74,565,484)	17,150,061	$ 50	50,602,666	(6,812,757)	34,994,216	(620,940,838)
2031	90%	$60.00	128,288,448	-	-	(79,989,568)	(81,057,391)	(161,046,959)	5.90%	(41,806,973)	(74,565,484)	17,150,061	$ 50	50,602,666	(6,812,757)	34,994,216	(610,993,298)
2032	90%	$60.00	128,288,448	-	-	(79,989,568)	(81,057,391)	(161,046,959)	5.91%	(41,877,832)	(74,636,343)	17,166,359	$ 50	50,602,666	(6,867,318)	35,010,514	(602,339,234)
2033	90%	$60.00	128,288,448	-	-	(79,989,568)	(81,057,391)	(161,046,959)	5.90%	(41,806,973)	(74,565,484)	17,150,061	$ 50	50,602,666	(6,812,757)	34,994,216	(594,817,464)
2034	90%	$60.00	128,288,448	-	-	(79,989,568)	(81,057,391)	(161,046,959)	5.91%	(41,877,832)	(74,636,343)	17,166,359	$ 50	50,602,666	(6,867,318)	35,010,514	(588,273,749)
2035	90%	$60.00	128,288,448	-	-	(79,989,568)	(81,057,391)	(161,046,959)	5.90%	(41,806,973)	(74,565,484)	17,150,061	$ 50	50,602,666	(6,812,757)	34,994,216	(582,586,211)
2036	90%	$60.00	128,288,448	-	-	(79,989,568)	(81,057,391)	(161,046,959)	5.91%	(41,877,832)	(74,636,343)	17,166,359	$ -	-	(57,469,984)	(15,592,152)	(584,789,829)
2037	90%	$60.00	128,288,448	-	-	(79,989,568)	(81,057,391)	(161,046,959)	5.90%	(41,806,973)	(74,565,484)	17,150,061	$ -	-	(57,415,422)	(15,608,450)	(586,708,021)
2038	90%	$60.00	128,288,448	-	-	(79,989,568)	(81,057,391)	(161,046,959)	5.91%	(41,877,832)	(74,636,343)	17,166,359	$ -	-	(57,469,984)	(15,592,152)	(588,374,273)
2039	90%	$60.00	128,288,448	-	-	(79,989,568)	(81,057,391)	(161,046,959)	2.95%	(20,903,486)	(53,661,997)	12,342,259	$ -	-	(41,319,738)	(20,416,251)	(590,271,471)
2040	90%	$60.00	128,288,448	-	-	(79,989,568)	(81,057,391)	(161,046,959)	0.00%	-	(32,758,511)	7,534,457	$ -	-	(25,224,053)	(25,224,053)	(592,309,704)
2041	90%	$60.00	128,288,448	-	-	(79,989,568)	(81,057,391)	(161,046,959)	0.00%	-	(32,758,511)	7,534,457	$ -	-	(25,224,053)	(25,224,053)	(594,082,080)
2042	90%	$60.00	128,288,448	-	-	(79,989,568)	(81,057,391)	(161,046,959)	0.00%	-	(32,758,511)	7,534,457	$ -	-	(25,224,053)	(25,224,053)	(595,623,276)
2043	90%	$60.00	128,288,448	-	16,747,941	(79,989,568)	(81,057,391)	(161,046,959)	0.00%	-	(32,758,511)	7,534,457	$ -	-	(25,224,053)	(8,476,112)	(596,073,618)

NGCC with CDR

Year	Percentage of Design Capacity	Electricity Price ($/MW-hr)	Sales	Capital Costs	Working Capital	Var Costs	Fixed Costs	Total Costs	15 year MACRS	Depreciation	Taxible Income	Taxes	CO2 Credit ($/tonne CO2)	CO2 Credit	Net Earnings	Cash Flow	Cumulative Net Present Value
2022	0%	$60.00	-	-	-	-	-	-		-	-	-	$ -	-	-	-	-
2023	0%	$60.00	-	(863,246,267)	(8,634,427)	-	-	-		-	-	-	$ -	-	-	(871,880,694)	(758,157,125)
2024	45%	$60.00	64,144,224	-	(4,317,214)	(38,041,498)	(87,800,815)	(125,842,313)	5.00%	(38,537,780)	(100,235,869)	23,054,250	$ 43	23,779,048	(53,402,571)	(19,182,005)	(772,661,477)
2025	68%	$60.00	96,216,336	-	(4,317,214)	(57,062,247)	(87,800,815)	(144,863,062)	9.50%	(73,221,782)	(121,868,508)	28,029,757	$ 47	38,418,007	(55,420,744)	13,483,824	(763,795,644)
2026	90%	$60.00	128,288,448	-	-	(76,082,997)	(87,800,815)	(163,883,812)	8.55%	(65,899,603)	(101,494,967)	23,343,842	$ 50	54,878,947	(23,272,177)	42,627,426	(739,423,275)
2027	90%	$60.00	128,288,448	-	-	(76,082,997)	(87,800,815)	(163,883,812)	7.70%	(59,348,181)	(94,943,544)	21,837,015	$ 50	54,878,947	(18,227,582)	41,120,599	(718,979,070)
2028	90%	$60.00	128,288,448	-	-	(76,082,997)	(87,800,815)	(163,883,812)	6.93%	(53,413,363)	(89,008,726)	20,472,007	$ 50	54,878,947	(13,657,772)	39,755,591	(701,791,631)
2029	90%	$60.00	128,288,448	-	-	(76,082,997)	(87,800,815)	(163,883,812)	6.23%	(48,018,074)	(83,613,437)	19,231,091	$ 50	54,878,947	(9,503,399)	38,514,674	(687,312,539)
2030	90%	$60.00	128,288,448	-	-	(76,082,997)	(87,800,815)	(163,883,812)	5.90%	(45,474,580)	(81,069,944)	18,646,087	$ 50	54,878,947	(7,544,909)	37,929,671	(674,913,262)
2031	90%	$60.00	128,288,448	-	-	(76,082,997)	(87,800,815)	(163,883,812)	5.90%	(45,474,580)	(81,069,944)	18,646,087	$ 50	54,878,947	(7,544,909)	37,929,671	(664,131,282)
2032	90%	$60.00	128,288,448	-	-	(76,082,997)	(87,800,815)	(163,883,812)	5.91%	(45,551,656)	(81,147,019)	18,663,814	$ 50	54,878,947	(7,604,258)	37,947,398	(654,751,266)
2033	90%	$60.00	128,288,448	-	-	(76,082,997)	(87,800,815)	(163,883,812)	5.90%	(45,474,580)	(81,069,944)	18,646,087	$ 50	54,878,947	(7,544,909)	37,929,671	(646,598,540)
2034	90%	$60.00	128,288,448	-	-	(76,082,997)	(87,800,815)	(163,883,812)	5.91%	(45,551,656)	(81,147,019)	18,663,814	$ 50	54,878,947	(7,604,258)	37,947,398	(639,505,900)
2035	90%	$60.00	128,288,448	-	-	(76,082,997)	(87,800,815)	(163,883,812)	5.90%	(45,474,580)	(81,069,944)	18,646,087	$ 50	54,878,947	(7,544,909)	37,929,671	(633,341,268)
2036	90%	$60.00	128,288,448	-	-	(76,082,997)	(87,800,815)	(163,883,812)	5.91%	(45,551,656)	(81,147,019)	18,663,814	$ -	-	(62,483,205)	(16,931,549)	(635,734,181)
2037	90%	$60.00	128,288,448	-	-	(76,082,997)	(87,800,815)	(163,883,812)	5.90%	(45,474,580)	(81,069,944)	18,646,087	$ -	-	(62,423,857)	(16,949,277)	(637,817,154)
2038	90%	$60.00	128,288,448	-	-	(76,082,997)	(87,800,815)	(163,883,812)	5.91%	(45,551,656)	(81,147,019)	18,663,814	$ -	-	(62,483,205)	(16,931,549)	(639,626,540)
2039	90%	$60.00	128,288,448	-	-	(76,082,997)	(87,800,815)	(163,883,812)	2.95%	(22,737,290)	(58,332,654)	13,416,510	$ -	-	(44,916,143)	(22,178,853)	(641,687,530)
2040	90%	$60.00	128,288,448	-	-	(76,082,997)	(87,800,815)	(163,883,812)	0.00%	-	(35,595,364)	8,186,934	$ -	-	(27,408,430)	(27,408,430)	(643,902,271)
2041	90%	$60.00	128,288,448	-	-	(76,082,997)	(87,800,815)	(163,883,812)	0.00%	-	(35,595,364)	8,186,934	$ -	-	(27,408,430)	(27,408,430)	(645,828,133)
2042	90%	$60.00	128,288,448	-	-	(76,082,997)	(87,800,815)	(163,883,812)	0.00%	-	(35,595,364)	8,186,934	$ -	-	(27,408,430)	(27,408,430)	(647,502,796)
2043	90%	$60.00	128,288,448	-	17,268,855	(76,082,997)	(87,800,815)	(163,883,812)	0.00%	-	(35,595,364)	8,186,934	$ -	-	(27,408,430)	(10,139,575)	(648,041,519)

Allam Cycle